Fundamentals and Improvements for Directional Relays

Karl Zimmerman and David Costello
Schweitzer Engineering Laboratories, Inc.

Revised edition released October 2010

Previously presented at the
37th Annual Western Protective Relay Conference, October 2010

Originally presented at the
63rd Annual Conference for Protective Relay Engineers, March 2010

Fundamentals and Improvements for Directional Relays

Karl Zimmerman and David Costello, *Schweitzer Engineering Laboratories, Inc.*

***Abstract*—Phase and ground directional elements are relied on for fast and secure protection throughout the power system. Although directional relays have been applied successfully for many years, several new and unique applications and power system disturbances present challenges.**

Using field and laboratory data, this paper reviews fundamentals, discusses the limits to sensitivity, and shows how and why directional element designs have progressed. The paper also describes how directional elements are applied during loss of voltage conditions.

In addition to design basics, we show several practical field examples that illustrate problems and solutions, while providing guidance on applying and setting modern directional relays.

I. Introduction

Directional elements determine the fault direction. They are used to control overcurrent elements, supervise distance elements for increased security, and form quadrilateral distance characteristics. Generally, directional elements are not applied alone, although they can be in unique applications.

Directional elements respond to the phase shift between a polarizing quantity and an operate quantity. In Fig. 1, the faulted phase voltage, V, is the polarizing quantity, and the faulted phase current, I, is the operate quantity. Because lines are predominantly inductive, I lags V by the fault loop impedance angle, ϕ_F, for forward line faults. For reverse faults on the adjacent line, I leads V by approximately 180 degrees minus the fault loop impedance angle, ϕ_R. The polarizing quantity may be called the reference quantity, which reinforces the need for it to be a stable and reliable signal, no matter where the fault is located.

The options for selecting polarizing and operate signals vary and include voltage or current signals or phase (VA or IA), phase pairs (VAB or IAB), or symmetrical component quantities (I_1, I_2, or I_0). When determining which signals to choose, designers and application engineers must consider ease of implementation, cost, security, and sensitivity.

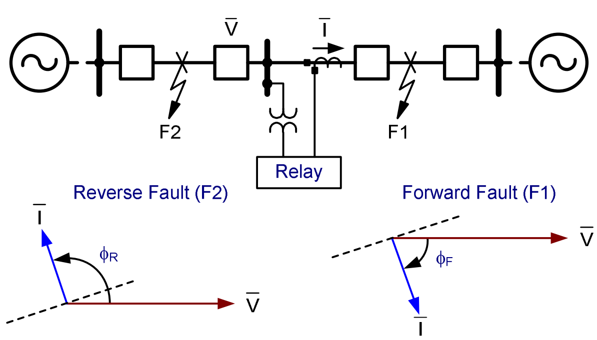

Fig. 1. Basic directional element principle

II. Evolution of Directional Elements

A. Electromechanical Relay Design

Electromechanical induction cup relays were essentially two-phase motors with two coils of wire wound around four poles of an electromagnet, as shown in Fig. 2. Polarizing and operate quantities were applied individually to the two windings. In the center was a magnetic core with a movable cup with contacts and a spring to provide reset tension. The relay was designed such that no rotational movement or torque occurred when the magnetic fluxes of the two coils were in phase [1].

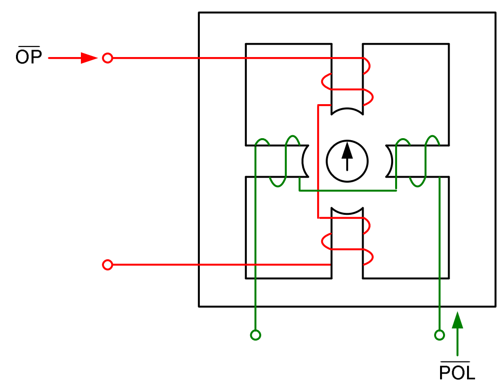

Fig. 2. Typical electromechanical induction cup relay

The terms *maximum torque angle* and *zero torque angle* have roots in electromechanical designs but are still commonplace today. In Fig. 1, the magnitude of angle ϕ_F represents the maximum torque angle for a forward direction fault.

Consider a typical electromechanical phase directional relay. The directional element is “quadrature” polarized, meaning the A-phase relay uses A-phase current and VBC voltage. The relay is built such that the angle of maximum torque occurs for phase current lagging the unity power position by 45 degrees or leading the quadrature voltage by 45 degrees. At the maximum torque angle, the relay picks up at 1 percent of rated voltage with 2 A of current. With a rated voltage of 115 V, this represents a maximum or limit to sensitivity of 2.3 VA (i.e., 1.15 V and 2 A) [2].

The well-known torque expression for this relay is shown in its general form as (1). This is a power equation, and because of the quantities used, the directional element responds to both power flow and fault current.

$$T32P = k \cdot |VBC| \cdot |IA| \cdot \cos(\beta - 90) \quad (1)$$

where:

T32P is the torque product of the directional element.

k is the design constant.

VBC is the BC phase-to-phase voltage.

IA is the A-phase current.

β is the measured angle between VBC and IA.

A. R. Van C. Warrington first identified a security weakness of the quadrature-polarized phase directional element. For a reverse phase-to-ground fault when remote infeed current is largely zero-sequence, the directional element may misoperate [3]. This is not an issue on longer lines or those in which the phase element is not required to operate for ground faults.

Because negative- and zero-sequence quantities are usually only present in substantial levels during unbalanced, faulted conditions on a power system, they are often used to determine the direction of a fault on the system. Negative sequence can be used to detect phase-to-phase, phase-to-ground, and phase-to-phase-to-ground faults. Zero sequence can be used to detect phase-to-ground and phase-to-phase-to-ground faults [4]. With electromechanical designs, negative-sequence relays in particular were slightly more complicated and costly to implement.

Zero-sequence, current-polarized directional elements use the neutral current from a local power transformer with a grounded neutral as the polarizing quantity. The operate quantity is the protected line ground current. Maximum torque develops when these two currents are in phase. Care is required to verify that the polarizing current always flows in a consistent direction to the system, regardless of the ground fault location [5]. Ground relays are also implemented using zero-sequence voltage as the polarizing quantity. In some applications, the zero-sequence voltage may be too small to overcome the minimum torque requirement, or the neutral current is eliminated when the transformer is taken out of service. In these cases, a dual-polarized directional element is applied where either zero-sequence voltage or current provides the directional decision. Zero-sequence voltage elements are especially susceptible to voltage transformer (VT) grounding errors. Zero-sequence current elements are vulnerable to incorrect polarity of the neutral current transformer (CT). This is no different than any directional application; however, in many cases, the neutral CT is inside the transformer and requires a primary injection test to validate its polarity. With either zero-sequence current- or voltage-polarized elements, mutual coupling due to parallel lines can cause application problems.

Negative-sequence voltage polarization is preferred for the following reasons. For most transmission lines, the negative-sequence source at the relay location provides a larger signal. The V_2 magnitude at the relay location is smaller with a smaller Z_2 (stronger) source and larger with a larger Z_2 (weaker) source. Also, these elements are immune to zero-sequence mutual coupling problems and less affected by VT neutral shift. A separate polarizing CT is not required. Lastly, only two VTs are required [6].

When using electromechanical relays, the application engineer needs to decide to apply either zero- or negative-sequence directional control before ordering.

B. Early Microprocessor-Based Relay Design (1980s)

Early microprocessor-based directional elements ushered in a wave of innovations. The microprocessor design lowered costs, improved design and installation ease, and allowed for computational solutions to problems mentioned previously.

Fig. 3 shows the phase and negative-sequence quantities presented to the relay for a forward fault with no load current. For a reverse fault, the angle of the fault current reverses polarity.

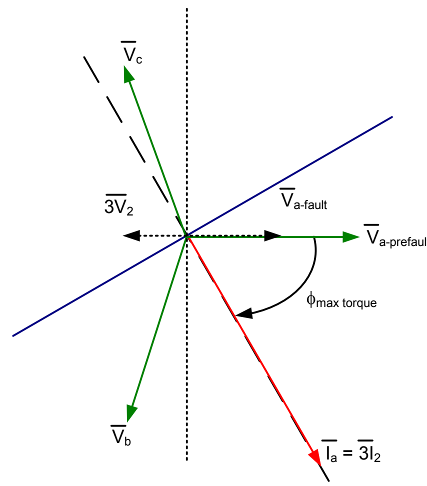

Fig. 3. Phase and negative-sequence signals for a forward fault with no load current

An early microprocessor-based, negative-sequence directional element was implemented using (2). The minimum torque required to operate is 0.10 VA, which is a dramatic sensitivity improvement over electromechanical designs [7]. The cosine term produces a sign used by the relay to determine direction. Forward faults are represented by positive torque products. Reverse faults are represented by negative torque products. As the fault current angle rotates ±90 degrees, the torque product decreases to zero. At the angles as shown in Fig. 3, or for a reverse fault, the cosine term produces maximum torque.

$$T32Q = |V_2| \cdot |I_2| \cdot \cos\left[\angle -V_2 - \left(\angle I_2 + \angle MTA\right)\right] \quad (2)$$

where:

T32Q is the torque product of the negative-sequence directional element.

V_2 is the negative-sequence voltage.

I_2 is the negative-sequence current.

MTA is the maximum torque angle setting.

Microprocessor-based relays also offer the user the choice of independently applying a negative-sequence voltage, zero-sequence voltage, zero-sequence current, or dual zero-sequence, polarized directional element—all in one product. This simplifies purchasing and stocking of spares because one relay can be used for many different applications.

Recall Warrington's application concern. An early microprocessor-based relay solved this problem with several new innovations. First, for balanced faults, a new positive-sequence, voltage-polarized directional element was implemented. For Warrington's case of a nearly pure zero-sequence source condition, the minimum positive-sequence torque is not overcome, and the element remains secure. Second, dependability during zero-voltage balanced faults was improved by using a memory voltage. Third, a negative-sequence directional element was implemented for phase directional control in addition to being available for ground faults. Fourth, a combined phase directional torque was created by adding the positive-sequence torque with four times the negative-sequence torque [8]. This combined phase torque element improved security for phase-to-phase faults on adjacent lines with heavy load [3].

C. Microprocessor-Based Relay Evolution (1993)

When the source behind the relay is strong, the voltage measured at the relay location for a remote fault can be too small to overcome the minimum torque requirements of a torque-product directional element. In 1993, a new approach was introduced using the ratio of negative-sequence voltage and current (or negative-sequence impedance, Z_2) rather than the product, as shown in (3) [9]. Using calculated negative-sequence voltage and current applied to the relay, the new directional element calculates the magnitude of negative-sequence impedance that lies collinearly to the protected positive-sequence line impedance.

$$Z_{2\text{measured}} = \frac{\text{Re}\left[V_2 \bullet \left(1\angle \text{Z1ANG} \bullet I_2\right)^*\right]}{\left|I_2\right|^2} \qquad (3)$$

where:

V_2 is the negative-sequence voltage.

I_2 is the negative-sequence current.

$\angle$Z1ANG is the positive-sequence line angle.

* indicates complex conjugate.

Consider Fig. 4. For a fault in front of the relay, the $Z_{2\text{measured}}$ equals $-Z_{S2}$ (the source impedance behind the relay). For a fault behind the relay, the $Z_{2\text{measured}}$ equals $Z_{L2} + Z_{R2}$ (the line impedance plus the remote source impedance).

By comparing the $Z_{2\text{measured}}$ to thresholds, this new element yields the fault direction. If $Z_{2\text{measured}}$ is less than threshold Z_{F2}, the fault is forward. If $Z_{2\text{measured}}$ is greater than threshold Z_{R2}, the fault is reverse.

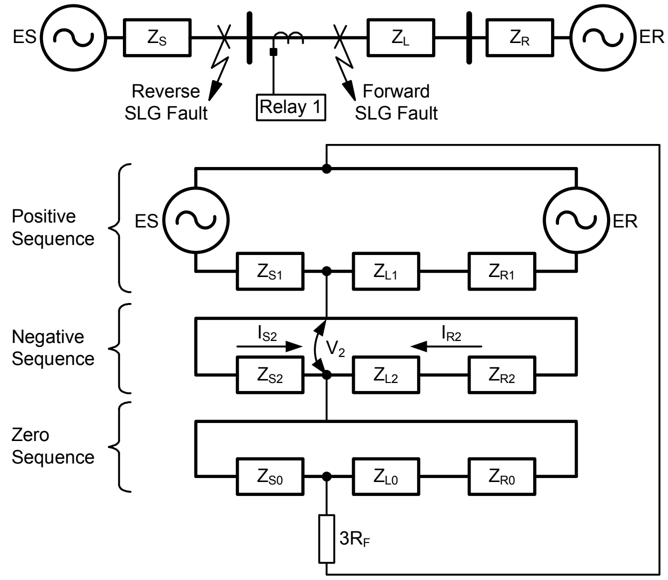

Fig. 4. Symmetrical component diagram for single-line-to-ground (SLG) faults

Previous directional element designs were limited when the negative-sequence voltage was too low, making the negative-sequence $Z_{2\text{measured}}$ near zero. In the 1993 design, the threshold Z_{F2} was increased to improve sensitivity (see Fig. 5).

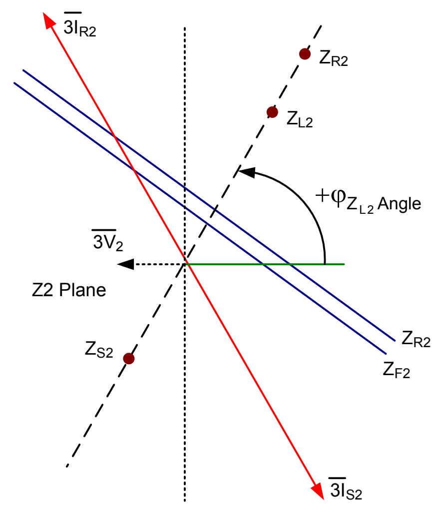

Fig. 5. Measured negative-sequence impedance yields fault direction

A positive-sequence restraint factor, the ratio of $|I_{A2}|$ divided by $|I_{A1}|$, must be exceeded to allow the directional element to operate. This prevents the element from misoperating during three-phase faults on nontransposed lines. Lastly, the magnitude of negative-sequence current, $|3I2|$, must exceed minimum fault detector settings to ensure that the directional element is disabled for unbalanced power system or load conditions.

Reference [10] introduced a novel way of expressing the sensitivity of relays and protection systems by their maximum fault resistance coverage. The sample system of Fig. 6 was used, assuming no load and 90-degree impedance angles.

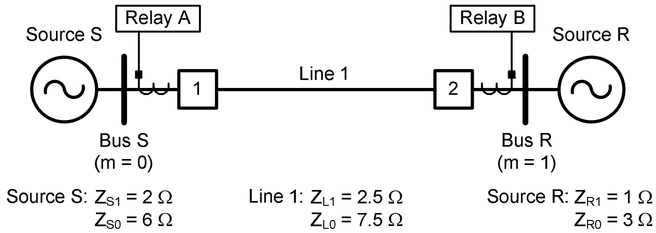

Fig. 6. Example system to evaluate directional element performance

A single-line-to-ground fault with fault resistance, R_F, is placed at Bus S. Realize that R_F is an order of magnitude greater than the protected line. Therefore, the calculations are simplified by ignoring the system impedances, and the total fault I_2 equals V_A divided by $3R_F$. With the 1993 directional element, the minimum |3I2| setting is 0.25 A. Assuming a nominal V_A of 67 V, we solve for R_F and calculate 268 Ω. This is shown in Fig. 7 as Relay A with the remote breaker open. If the remote breaker is closed, the total fault I_2 will distribute according to system impedances and the fault location.

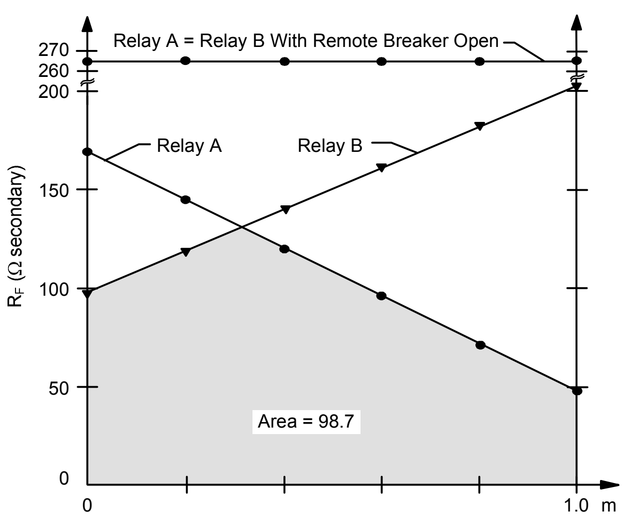

Fig. 7. R_F coverage depends on relay, system, and fault location

In a permissive overreaching transfer trip scheme, both relays must be able to see the fault in order to allow a high-speed trip. The shaded area in Fig. 7 represents the sensitivity of the protection system with 1993-era relays at each line terminal. What would happen if we replaced Relay B with a commonly applied electromechanical ground directional relay? The particular relay has a zero-sequence, voltage-polarized directional element that requires torque to exceed 2 VA, 3I0 greater than 2 A, and 3V0 greater than 1 V. Using this relay would reduce the system sensitivity to an area of 19.5, an 80 percent reduction in R_F coverage.

Reference [11] provides evidence of the need for improved sensitivity through a case study of a 500 Ω fault on a 525 kV transmission line in Brazil. The cause of the fault was a flashover from the transmission line to trees near a river crossing. There was practically no voltage dip on the faulted phase, V_2 of 0.54 V (see Fig. 8). With such high fault impedance, the angular difference between the faulted phase voltage and current was between –5 and –10 degrees. The ratio of $|I_{A2}|$ to $|I_{A1}|$ was 0.23, and |3I2| was 0.82 A. The directional element implemented in 1993 saw this fault and operated correctly.

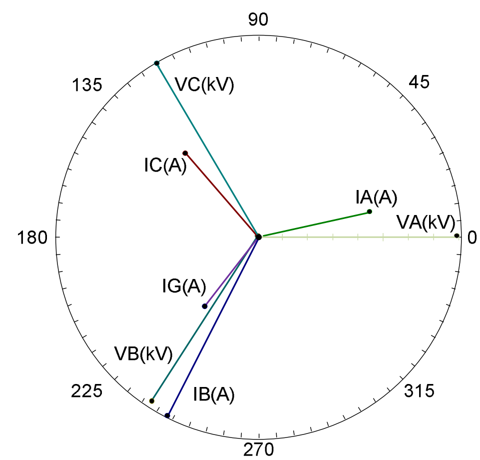

Fig. 8. Voltage and current phasors for 525 kV BG fault with 500 Ω R_F

Consider a typical electromechanical ground directional relay. The directional element operates on negative-sequence current and voltage, while the overcurrent unit operates on zero-sequence or ground current. The directional unit minimum pickup is approximately 0.76 VA (i.e., 0.19 V and 4 A) in terms of negative-sequence quantities applied at the relay terminals at the maximum torque angle of approximately 98 degrees (current leading voltage) [12]. This relay would not have seen this transmission line fault because it produced 0.14 VA, less than 20 percent of that required by the relay to operate.

D. *Microprocessor-Based Relay Evolution (1996)*

Calculating thresholds Z_{F2} and Z_{R2} in the 1993 relay requires running fault studies and careful analysis. Thresholds were set to detect unbalanced faults under the strongest anticipated negative-sequence source conditions. The following case study exemplifies the potential for settings errors.

A 138 kV bus fault caused by a surge arrestor failure at a remote substation was cleared by high-impedance bus differential relays. The transmission line is protected by a directional comparison blocking (DCB) scheme. The local relay never received a blocking signal and misoperated by tripping for the remote bus fault. Using the voltages and currents at the time of trip shown in Fig. 9, we can calculate the negative-sequence source impedance, Z_{S2}, behind the local relay during the remote bus fault (–4.125 Ω).

```
Local Relay 138KV-DCB          Date: 09/22/96 Time: 05:56:20.878
FID=XXX-XXX-R407-V656112pb-D940927
   CURRENTS (pri)       VOLTAGES (kV pri) RELAY    ELEMENTS  OUT  IN
                                          ZZZZZZO   555566L  1357 1357
                                          ABCABCO  3111077O  &&&& &&&&
  IR   IA    IB    IC    VA    VB    VC   BCAGGGS  2NQPPNQP  2468 2468

  861   2    59   800  92.2   8.0  -3.9   .....4.  Qpp.H.... ..5. 13..
-1806 -48  -117 -1642 -19.8  94.9  -5.4   .....4.  Qpp.H.... ..5. 13..
 -848  -3   -61  -784 -92.0  -7.9   3.9   .....4.  Qpp.H.... ..5. 13..
 1806  48   116  1642  19.8 -94.6   5.5   .....2.  Qpp.H.... 135. 13..
```

Fig. 9. Voltages and currents seen by local relay for remote bus fault

The relay at the remote end of the line did not generate event data. However, recall from Fig. 4 that, for a reverse fault, a relay will measure $Z_{L2} + Z_{R2}$ (i.e., the line impedance plus the remote source impedance). To estimate the negative-sequence impedance seen by the remote relay during the bus fault, realize that the local relay Z_{S2} is equal to the remote relay Z_{R2}. The local relay settings indicate that the positive-sequence line impedance is 0.25 Ω (assume $Z_{L1} = Z_{L2}$). Therefore, the remote relay should have a $Z_{2measured}$ of +4.375 Ω. This value would have been compared against the relay setting thresholds of the negative-sequence impedance directional element ($Z_{F2} = 1$ Ω, and $Z_{R2} = 5$ Ω). Because Z_2 was not greater than Z_{R2}, the directional element in the remote relay did not declare a reverse fault direction. This explains the failure to send a blocking signal to the local relay for the reverse bus fault [13].

In 1996, a new version of the negative-sequence impedance directional element was introduced that automatically calculates directional thresholds [14]. This new "automatic" setting uses the positive-sequence line impedance data and the following observation from Fig. 4. For a reverse fault, the relay should always measure a Z_2 equal to the line impedance in front of the relay. So the new relay automatically set $Z_{F2} = 0.5 \cdot Z_{L1}$ Ω and $Z_{R2} = Z_{F2} + 0.1$ Ω. From the previous case study, we see that if the relay had an automatic setting, Z_{R2} would have been set to 0.225 Ω, and the $Z_{2measured}$ would have clearly been in the reverse region, thus allowing correct operation. The automatically calculated thresholds offer a dramatic improvement by reducing settings calculations and the potential for errors. The relay is also equipped with a zero-sequence, impedance-based directional element that operates in a similar fashion using zero-sequence quantities.

The same 1996-era relay also introduced a best choice ground directional element [15]. This new relay allows the user to select a preference or order (ORDER) of directional element operating characteristics. The selection options are negative-sequence impedance, Q, zero-sequence impedance, V, and current polarized, I. For example, we might chose ORDER = QV, which means that the relay uses a negative-sequence impedance, voltage-polarized element first, assuming there is sufficient negative-sequence current. However, if there is not, the relay then uses a zero-sequence impedance, voltage-polarized element to make the directional decision. The next case study exemplifies the benefit of the best choice element for changing system conditions.

A generator was offline. The generator step-up transformer was fed radially from a single 138 kV tie line to a local utility. The line was protected by a DCB scheme. A BG fault then occurred on the line. The relay at the generator end of the line saw this fault incorrectly as reverse and sent a blocking signal to the utility terminal, delaying fault clearing (see Fig. 10).

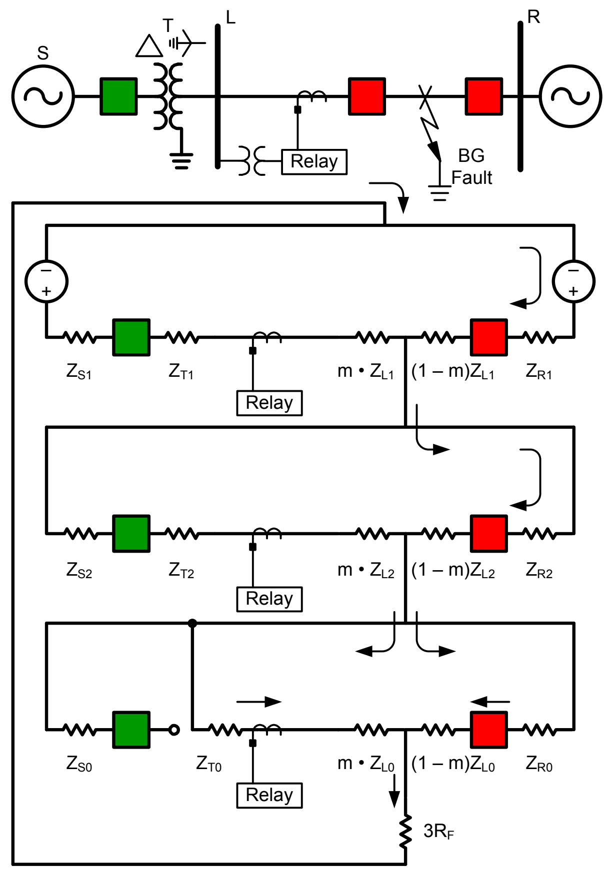

Fig. 10. Symmetrical component diagram for BG fault with generator offline

Event data from the relay at the generator end of the line are shown in Fig. 11. The phase currents are all in phase. With the generator breaker open, a pure zero-sequence source is behind the relay.

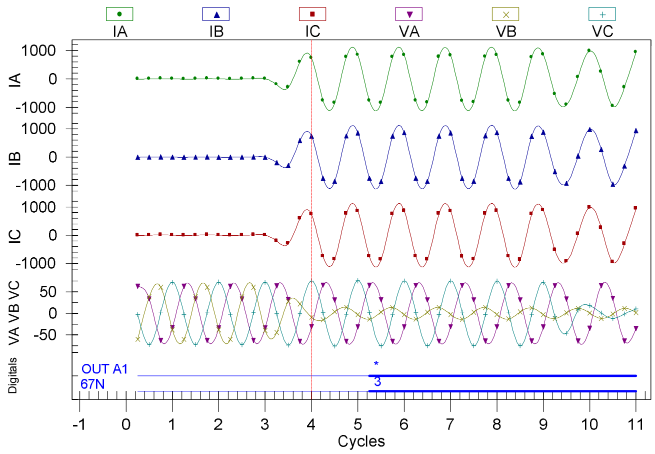

Fig. 11. Fault data from directional relay on generator side of tie line

The relay was a 1980s-era microprocessor design. Its directional element could be negative-sequence voltage polarization, zero-sequence voltage polarization, or current polarization. All methods were torque products. Only one element could be used at a time. The user had selected the negative-sequence element. With the local generation connected, negative-sequence polarization would have been reliable. However, with the generation isolated, the negative-sequence polarized element did not correctly determine the fault direction. This was because of the lack of negative-sequence current from the pure zero-sequence source (wye-grounded transformer) behind the relay. This incorrect direction decision keyed a blocking signal that delayed tripping.

By replaying the event data into a 1996-era microprocessor-based relay, we can prove that this relay, with automatic switching logic, would have correctly switched to a zero-sequence element. Zero-sequence voltage polarization correctly determines this to be a forward fault. Zero-sequence current polarization would have also correctly declared a forward fault for this event, because I_{POL} and 3I0 are in phase [16].

In the simulation, we chose an order that always gives preference to negative-sequence polarization (Q, V, I). In this case, there is little negative sequence, so the relay checks zero sequence and makes the proper forward directional declaration. This secure operation comes at the expense of a slight processing delay. Overall, this directional logic results in faster operating times for all system states. When the generation is online, the negative-sequence directional element operates most reliably, and when generation is offline, the zero-sequence element operates correctly (see Fig. 12).

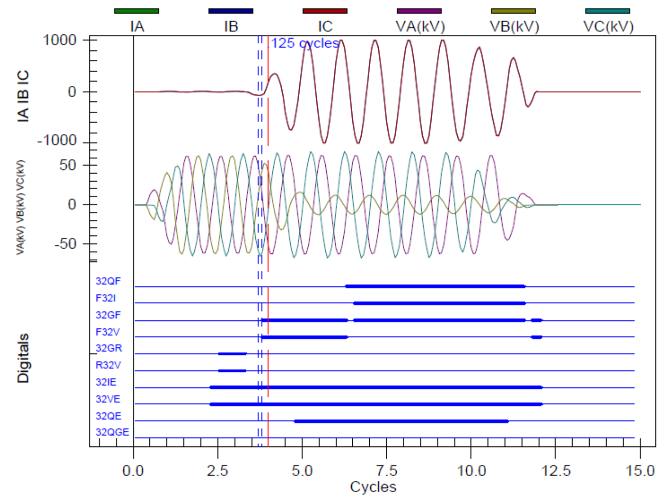

Fig. 12. Automatic switching ground directional element response

III. Field Case Studies

A. Low V_2 Magnitude Challenges Automatic Thresholds

Fig. 13 shows a one-line diagram of a three-terminal 345 kV system. However, the three-terminal line is not the challenge. The main concern is that the 69 kV system behind the south breaker is a very weak source and has a large transformer connected.

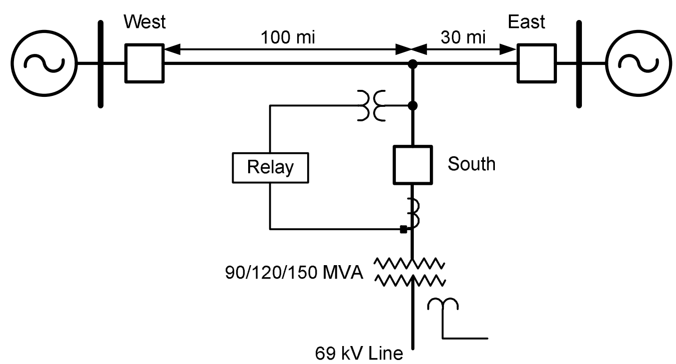

Fig. 13. Weak source and transformer terminal challenge automatic settings

Relays with a negative-sequence impedance directional element were applied in a DCB scheme. Because the south terminal is a weak source, the ground overcurrent pickup was set low. The line impedance setting was based on the impedance between the south and east buses. Directional thresholds were set automatically to $Z_{F2} = 0.5 \bullet Z_{L1}\ \Omega$ and $Z_{R2} = Z_{F2} + 0.1\ \Omega$.

The problem occurred when the autotransformer was energized from the line by closing the south breaker. The $V_{2measured}$ was small (less than 0.3 V), but 3I2 and 3I0 were large (4 to 5 A) because of phase unbalance during energization. The $Z_{2measured}$ plotted in the forward region (0.17 Ω secondary), and the local ground overcurrent picked up. Because no block signal was received from either of the remote terminals, the local DCB scheme tripped incorrectly during the transformer energization.

This exposes a weakness in the automatic settings method. That is, with little V_2 and the Z_{F2} forward directional threshold offset from the origin in the first quadrant (see Fig. 14), a forward fault is assumed. Sensitivity gained for sensing higher fault resistance comes with a security risk in some applications.

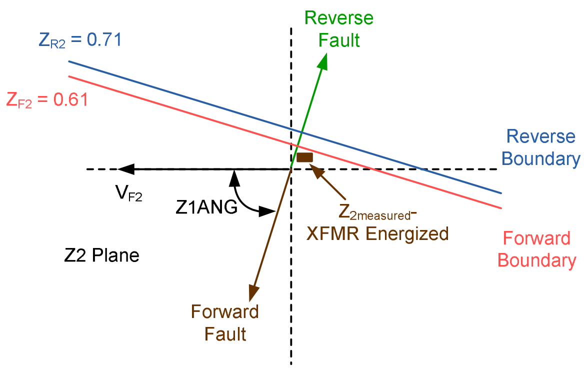

Fig. 14. A forward fault is declared with AUTO settings

Setting the Z_{F2} forward directional threshold to be slightly negative is the solution in this application (see Fig. 15). Internal line faults were simulated using a short-circuit program. The results were entered into a Mathcad® worksheet that emulates the directional element operation to ensure that the increased security still provided adequate sensitivity and dependability.

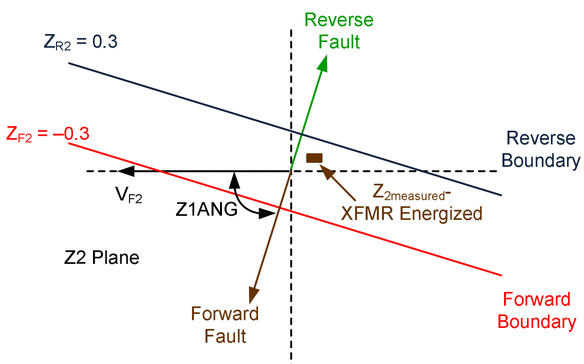

Fig. 15. A negative Z_{F2} setting increases security

B. Applications Without Lines Challenge Automatic Settings

Recall that the automatic settings calculate directional element thresholds from the positive-sequence line impedance entered by the user. What should an engineer do if the application of the directional relay does not involve a line? Consider the one-line diagram in Fig. 16.

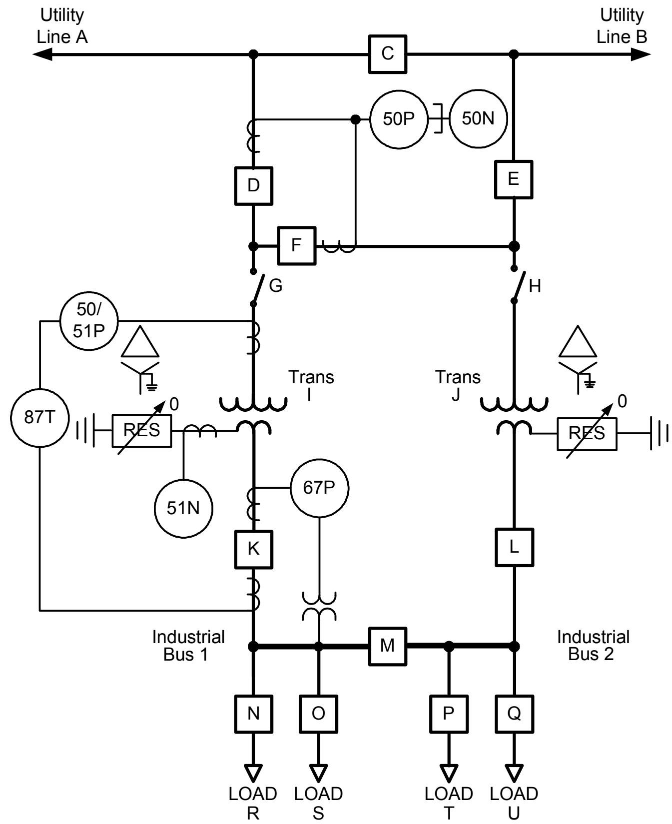

Fig. 16. 67P at the utility-industrial interface

The 67P relay is a directional phase overcurrent relay and is typically installed at the utility-industrial interface to trip for faults on the transformer high side that could be fed from the distribution bus as well as reverse power conditions [17]. Using power flow and fault current detection interchangeably implies the use of traditional (electromechanical or electromechanical-emulating) directional relays that rely on a torque product of voltage times current.

A misoperation occurred in a 1996-era relay when a remote utility system ground fault asserted the sensitively set negative-sequence impedance directional element at a time when power flowed into the industrial plant. Solutions implemented include the following:

- When a line impedance is not known, directional thresholds can be set centered about the origin, such as $Z_{F2} = –0.3\ \Omega$ and $Z_{R2} = +0.3\ \Omega$.
- A directional power element should be used to detect three-phase reverse power flow.
- A positive-sequence voltage-polarized phase overcurrent element with load-encroachment supervision should be used to detect high-side, three-phase faults.
- A negative-sequence voltage-polarized negative-sequence overcurrent element should be used to detect high-side, unbalanced faults [18].

C. Directional Element Operates for a Ground Fault on Adjacent Line When Element Switches From Z_2 to Z_0 Element

In Section II, Subsection D, we discussed a system where a negative-sequence impedance (Z_2 or Q) directional element could automatically switch to a zero-sequence impedance (Z_0 or V) directional element for improved dependability. In that example, there was not enough negative-sequence current flowing when the generator was offline. However, this automatic selection is not always desirable.

The 345 kV line shown in Fig. 17 connects the power plant at one terminal to the remote Substation R. This line is protected using a DCB scheme and has a parallel 138 kV line on the same right of way.

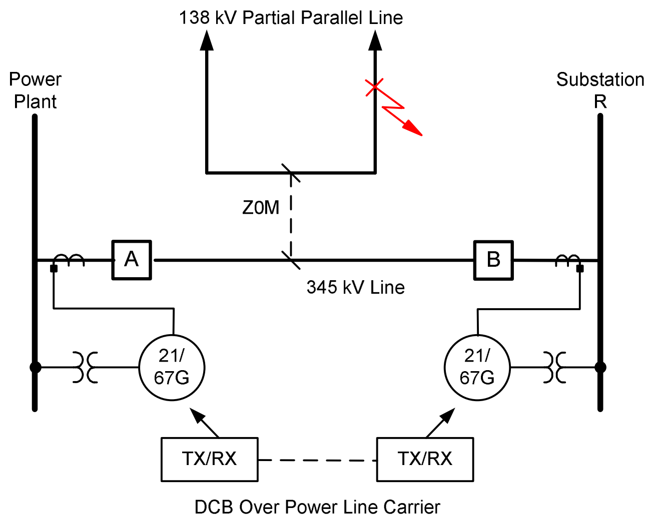

Fig. 17. 345 kV line with 138 kV line underbuild

In this case, a ground fault on the parallel line causes zero-sequence current to flow because of mutual coupling. As shown in Fig. 18 and Table I, the negative-sequence current is very low. Note that the phasor magnitudes are not to scale. There was very little negative-sequence current (3I2 = 111 A), so the directional element automatically switched to the zero-sequence directional element (3I0 = 407 A). As a result, the ground directional element (67G) at Breaker A asserted in the forward direction. This caused an undesired trip because no block was received from the remote terminal.

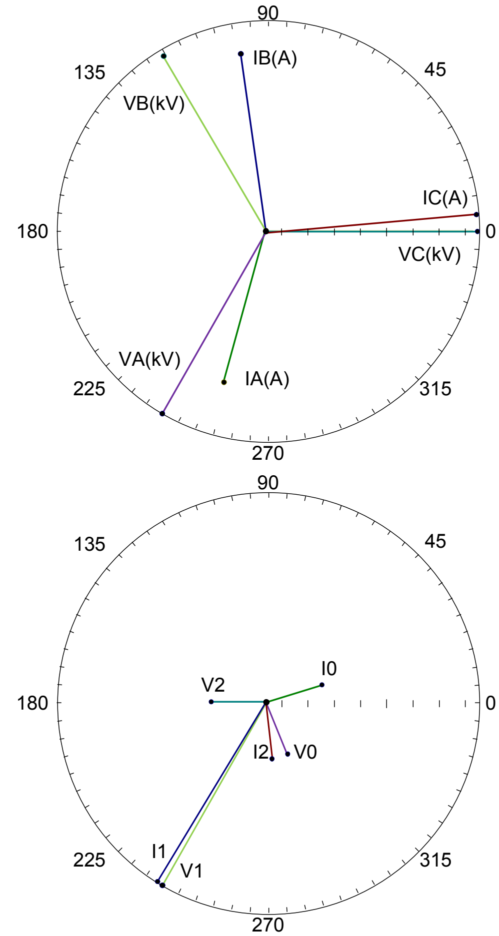

Fig. 18. Phase and sequence component phasors for Breaker A

TABLE I
PHASE AND SEQUENCE MAGNITUDE AND ANGLES FOR BREAKER A

Channel	Magnitude	Angle
IA(A)	442.1	253.2
IB(A)	507.6	99.1
IC(A)	597.1	4.3
IG(A)	407.5	17.7
VA(kV)	207.7	240.1
VB(kV)	202.9	120.2
VC(kV)	207.2	0.0
VS1(kV)	0.1	171.2
VS2(kV)	0.0	38.0
V1MEM(kV)	207.0	240.1
FREQ	60.0	n/a
I_0	135.6	17.6
I_1	500.1	238.7
I_2	37.3	275.0
V_0	1.7	290.7
V_1	206.0	240.1
V_2	1.4	179.4

The solution for this and similar applications is to disable zero-sequence directional elements. Zero-sequence elements, whether applied independently or in an automatic switching scheme, should be disabled when a possibility of mutual coupling due to parallel lines exists.

D. New Automatic Settings Recommendations

The automatic settings method introduced in 1996 (AUTO), described in Section II, Subsection D, assumes we are protecting a line with medium to strong sources at both ends. Using the system in Fig. 19, the forward Z_2 threshold, $Z_{F2,}$ is set to 0.5 • Z_{L1} (i.e., 0.5 • 2.5 = 1.25 Ω secondary). The reverse threshold, Z_{R2}, is Z_{F2} + 0.1 = 1.35 Ω secondary. If the $Z_{2\text{measured}}$ is less than 1.25 Ω, a forward fault is declared. If the $Z_{2\text{measured}}$ is greater than 1.35 Ω, a reverse fault is declared. Negative-sequence overcurrent pickup thresholds are selected as 0.25 A secondary, and the positive-sequence restraint factor a2 is set to 0.1. Negative-sequence impedance, Z_2, is assumed to be preferred with an automatic switch to zero-sequence impedance, Z_0, should 3I2 current be too small. This is done with a setting ORDER = QV.

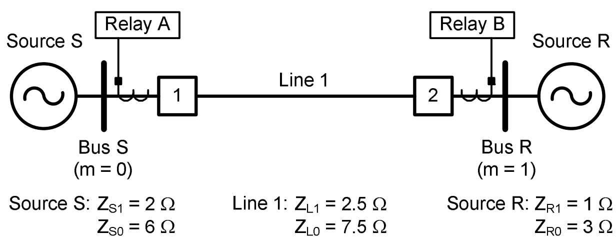

Fig. 19. Example system for calculating thresholds

A second method (AUTO2) does not assume a line (e.g., a transformer) and selects thresholds to allow load switching and transformer energization. The thresholds are selected as $Z_{F2} = -0.3$ Ω and $Z_{R2} = +0.3$ Ω (see Fig. 20). If the $Z_{2\text{measured}}$ is less than –0.3 Ω, a forward fault is declared. If the $Z_{2\text{measured}}$ is greater than +0.3 Ω, a reverse fault is declared. Note that the origin of the impedance plane, or $V_2 = 0$ V, is now an indeterminate point. In other words, this new AUTO2 method does not assume a zero or near-zero V_2 fault is forward (or reverse). Negative-sequence overcurrent pickup thresholds are selected as 0.25 A secondary, and the positive-sequence restraint factor a2 is set to 0.1. No automatic switching occurs (ORDER selects Q only).

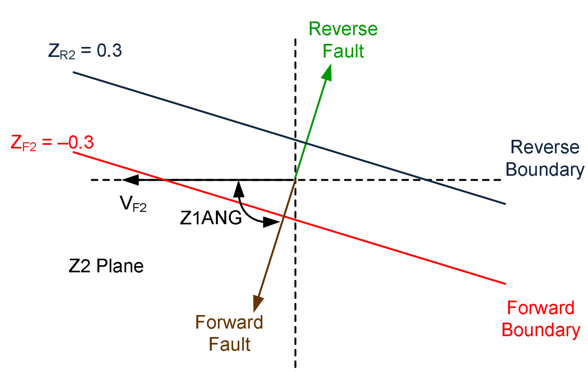

Fig. 20. New AUTO2 directional thresholds

The thresholds were determined to be a good balance between improved security and good sensitivity. In the field case in Section III, Subsection A, recall that the measured negative-sequence impedance for a nonfault condition was +0.17 Ω secondary.

Engineers should use a fault study to determine the worst-case Thévenin equivalent impedance (strongest source, lowest source impedance). In Fig. 19, this value is 2 Ω secondary. Thus, the $Z_{2\text{measured}}$ for any forward fault is –2 Ω secondary (adjusted for the positive-sequence line angle). This value becomes more negative if the source is weaker (Z_{S1} is higher). Using the strong source system shown in Fig. 21, the $Z_{2\text{measured}}$ for any forward fault is –0.2 Ω.

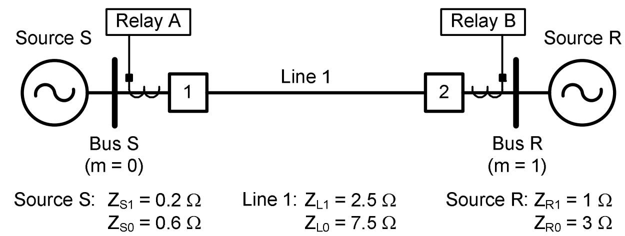

Fig. 21. Strong source system

Settings recommendations are as follows:

- If the strongest source (minimum source impedance) fault study Z_2 equivalent impedance is less than 0.5, use the AUTO method.
- If the strongest source Z_2 is greater than 0.5, use the AUTO2 method.
- For most systems, select ORDER = Q (i.e., to use only the negative-sequence impedance).

If a single contingency (loss of line or generator) can result in the loss of a negative-sequence source AND no zero-sequence mutual coupling is present, select the automatic switching scheme (ORDER = QV).

As with any protection scheme, we should understand what automatic settings imply and the assumptions that they make. If those assumptions are not understood, it is better to disable automatic settings and manually calculate setting thresholds based on the protected system.

IV. Directional Element Performance During Loss of Potential

A. Loss-of-Potential Detection

Valid voltage signals are necessary for the successful performance of voltage-polarized directional and distance elements. For this reason, electromechanical distance relays were commonly installed with overcurrent fault detectors in series for security during problems such as blown VT fuses.

Microprocessor-based relays include loss-of-potential (LOP) logic. This logic can be used to send an alarm through a SCADA (supervisory control and data acquisition) system so that root cause can be found quickly and protection quality restored. The following case study demonstrates a real-world LOP condition [13].

Both primary and backup relays at a 69 kV line terminal tripped for a VT fuse problem. The same VTs serve both relays (see Fig. 22). There was no system fault at the time of trip. The two microprocessor-based relays were different models. Both provided distance and directional overcurrent functions. The false apparent impedance created by abnormal voltages and load currents caused the apparent impedance to encroach on the reach of the distance relays.

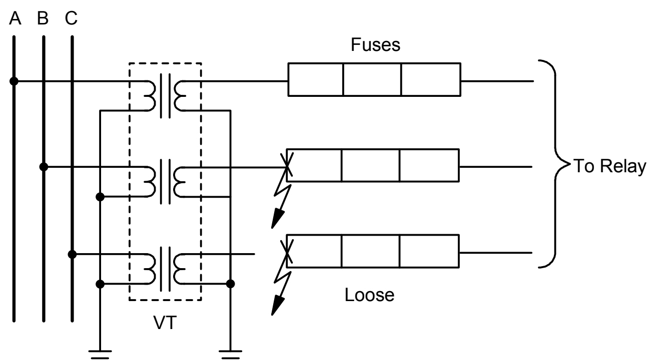

Fig. 22. VT fuse problem

Because a blown fuse results in a loss of polarizing inputs to the relays, detection of this condition was desirable and enabled in both relays. The event data show that the LOP detection asserted after the phase distance element tripped in each relay (see Fig. 23). In both relays, there was a three-cycle delay before the LOP element asserted for unbalanced conditions. This delay ensured that LOP would not block protection elements during a fault.

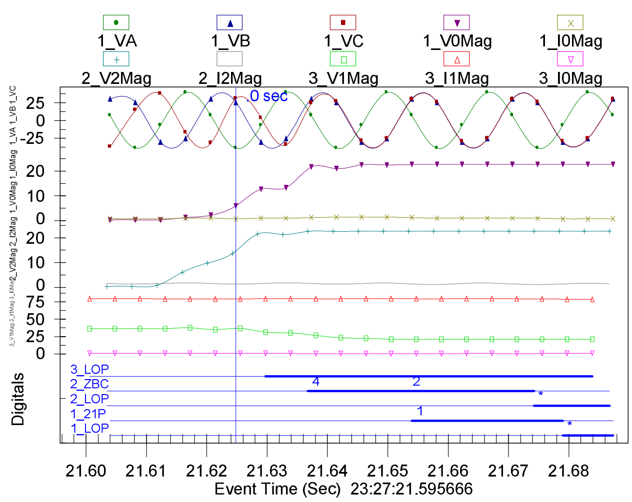

Fig. 23. Response of backup relay (1), primary relay (2), and 1996-era relay (3)

In the primary relay (a 1993-era relay), LOP was detected when negative-sequence voltage, V_2, was greater than 14 V secondary and negative-sequence current, 3I2, was less than 0.5 A secondary. In the backup relay (a 1980s-era relay) LOP was detected when zero-sequence voltage, V_0, was greater than 14 V secondary and zero-sequence current, I_0, was less than 0.083 A secondary. Once asserted, LOP blocked distance and directional elements that rely on healthy voltage signals.

This event emphasizes that early LOP logic was designed to protect distance elements from misoperating for system faults that occurred sometime after an initial LOP condition was detected. Overcurrent fault detectors, set above load, were used to prevent distance element misoperation when the LOP condition first occurred. In this event, the fault detectors (50L) were picked up during balanced load flow. Ideally, fault detectors should be set above expected load currents and below minimum fault levels to ensure correct distance relay operation.

Newer relays (starting in 1996) have LOP logic that operates based on the V_1 rate of change versus the rate of change of currents. The new logic operates in less than one-half cycle, so distance element security is less dependent on the fault detector settings. In Fig. 23, the response of the original relays is shown with that of a relay with improved LOP logic. The new relay LOP logic operates more than one cycle before any distance elements assert, ensuring this misoperation would not happen again.

B. *Patent-Pending Z1LOP Element*

NERC (North American Electric Reliability Corporation) has recently developed a standard that describes redundancy requirements for protection systems [19]. This document and other industry standards express the importance of maintaining protection system performance during the loss or failure of a component.

We avoid single points of failure by applying two completely redundant systems. This approach is used by many utilities and other industries (e.g., aviation). However, it may be cost-prohibitive or not possible (e.g., space limitations and legacy systems) to achieve two complete systems.

One important component failure is the loss of ac potential to the relay. During an LOP condition, SCADA alarms alert users to remedy the problem and restore voltages as quickly as possible. Users typically must choose to make the relays nondirectional or to disable the elements normally controlled by the directional element during the LOP condition.

Because most LOP conditions involve losing one or two VTs, we propose enabling a unique directional element when LOP is declared. This directional element uses the healthy voltage from the remaining voltage inputs to create a positive-sequence impedance element, Z1LOP. Directionality is stable for one or two blown VTs because the V_1 angle is stable, regardless of V_1 magnitude.

Z1LOP is enabled when LOP is declared and uses the measured positive-sequence impedance to compare against a threshold.

$$Z_{1measured} = \frac{\mathrm{Re}\left[(V_1)\bullet(I_1 \bullet \angle Z1ANG)^*\right]}{(|I_1|)^2} \qquad (4)$$

where:

V_1 is the positive-sequence voltage.

I_1 is the positive-sequence current.

$\angle$Z1ANG is the positive-sequence line angle.

* indicates complex conjugate.

A V_1 memory-polarized element is employed for three-phase fault conditions.

Use Z1LOP to torque-control phase and/or ground overcurrent elements (67, 67G) for time-delayed direct tripping or in pilot tripping schemes during LOP conditions.

We simulated hundreds of system faults to determine the reliability of Z1LOP. The element is directionally stable for all fault types, but sensitivity and security are limited as load and fault resistance increase.

Using the system model in Fig. 6, Fig. 24 and Fig. 25 show two common forward fault scenarios. In these figures, a positive value of $Z_{1measured}$ indicates a forward fault; a negative value indicates a reverse fault. It makes little difference for forward faults whether the blown VT fuse is on the faulted or unfaulted phase.

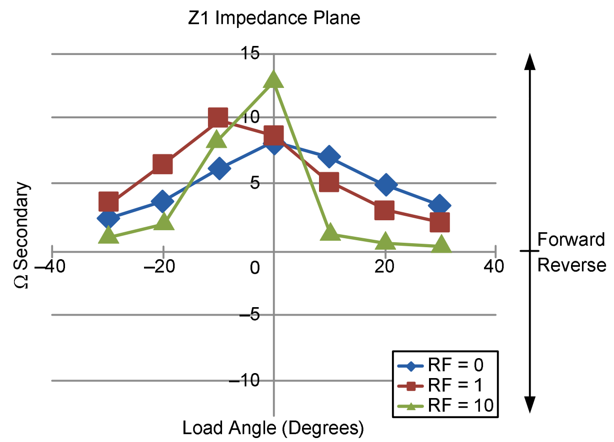

Fig. 24. $Z_{1measured}$ versus delta load angle with varying fault resistance for a forward midline CG fault with blown A-phase VT fuse

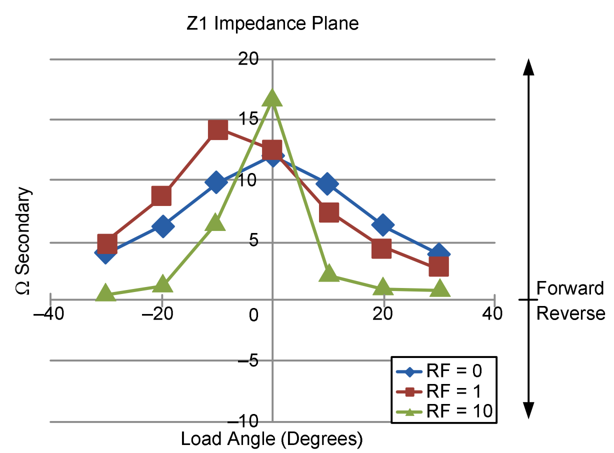

Fig. 25. $Z_{1measured}$ versus delta load angle with varying fault resistance for a forward midline AG fault with blown A-phase VT fuse

Reverse faults are most problematic if they occur on the same phase as the blown VT fuse. Z1LOP performs well, but as load and/or fault resistance increases, the element can be challenged. As seen in Fig. 26, the element may incorrectly declare forward if the load angle approaches 30 degrees and fault resistance exceeds 10 Ω secondary.

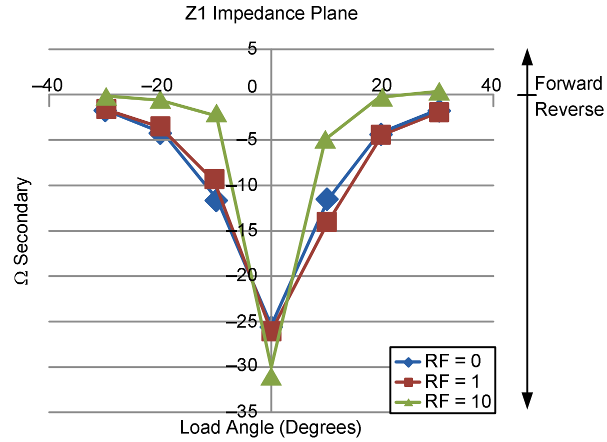

Fig. 26. $Z_{1measured}$ versus delta load angle with varying fault resistance for a reverse midline AG fault with blown A-phase VT fuse

Similar results occur for different fault types. Positive-sequence voltage memory elements perform well for three-phase faults.

To summarize, Z1LOP is not recommended when voltages are healthy. The element is active only during LOP conditions. However, it is a viable option for providing protection redundancy during LOP conditions for forward and reverse phase and ground faults, with some known limitations because of load and fault resistance.

Users should evaluate whether this solution works on their system. Dependability and security cannot be guaranteed under all conditions when the relay is not measuring accurate voltages. Dual complete systems or complementary protection schemes (i.e., line current differential) provide superior, albeit more costly, solutions.

V. Conclusions

Directional element designs continue to evolve as power systems challenge relays. Electromechanical and early microprocessor-based relays were less sensitive and could not easily respond to system changes. Newer designs are more sensitive and flexible, but sensitivity levels must be studied.

The application of directional relays on lines is different than directional relays on transformers. Each system must be evaluated.

Automatic settings for directional elements are helpful but can be misapplied if not clearly understood. They should be applied with caution and review, with an understanding of the assumptions made. The newer recommendations for using automatic settings included in this paper use the local positive-sequence source impedance as a guideline.

Users must decide how to protect the power system during LOP conditions. One solution is to consider applying a positive-sequence impedance directional element during LOP conditions. This element provides some protection to address the need for redundancy in protection systems.

VI. References

[1] J. L. Blackburn and T. J. Domin, *Protective Relaying Principles and Applications*, 3rd ed., H. L. Willis, Ed., New York: CRC Press, 2007, pp. 63, 175, 340, 453.

[2] *GE JBC51M Phase Directional Overcurrent Relays, Instruction Manual GEK-49848C*, GE Digital Energy Multilin. Available: http://www.gedigitalenergy.com/multilin/manuals.

[3] J. Roberts and A. Guzmán, "Directional Element Design and Evaluation," proceedings of the 21st Annual Western Protective Relay Conference, Spokane, WA, October 1994.

[4] B. Fleming, "Negative-Sequence Impedance Directional Element," proceedings of the 10th Annual Doble ProTest User Group Meeting, Pasadena, CA, February 1998.

[5] N. Fischer, D. Haas, and D. Costello, "Analysis of an Autotransformer Restricted Earth Fault Application," proceedings of the 61st Annual Conference for Protective Relay Engineers, College Station, TX, April 2008.

[6] K. Zimmerman and J. Mooney, "Comparing Ground Directional Element Performance Using Field Data," proceedings of the 20th Annual Western Protective Relay Conference, Spokane, WA, October 1993.

[7] SEL-221G5 Instruction Manual, Schweitzer Engineering Laboratories, Inc., Pullman, WA. Available: http://www.selinc.com.

[8] SEL-267-5 Instruction Manual, Schweitzer Engineering Laboratories, Inc., Pullman, WA. Available: http://www.selinc.com.

[9] SEL-321 Instruction Manual, Schweitzer Engineering Laboratories, Inc., Pullman, WA. Available: http://www.selinc.com.

[10] J. Roberts, E. O. Schweitzer, III, R. Arora, and E. Poggi, "Limits to the Sensitivity of Ground Directional and Distance Protection," proceedings of the 1997 Spring Meeting of the Pennsylvania Electric Association Relay Committee, Allentown, PA, May 1997.

[11] P. K. Maezono, E. Altman, K. Brito, V. Alves dos Santos Mello Maria, and F. Magrin, "Very High-Resistance Fault on a 525 kV Transmission Line – Case Study," proceedings of the 35th Annual Western Protective Relay Conference, Spokane, WA, October 2008.

[12] *ABB Type IRQ Directional Overcurrent Negative-Sequence Relay for Ground Protection*, Instruction Leaflet 41-133.2F, ABB, Coral Springs, FL. Available: http://www.abb.com.

[13] D. Costello, "Understanding and Analyzing Event Report Information," proceedings of the 55th Annual Georgia Tech Protective Relaying Conference, Atlanta, GA, April 2001.

[14] SEL-351 Instruction Manual, Schweitzer Engineering Laboratories, Inc., Pullman, WA. Available: http://www.selinc.com.

[15] A. Guzmán, J. Roberts, and D. Hou, "New Ground Directional Elements Operate Reliably for Changing System Conditions," proceedings of the 51st Annual Georgia Tech Protective Relaying Conference, Atlanta, GA, April 1997.

[16] D. Costello, "Lessons Learned Analyzing Transmission Faults," proceedings of the 34th Annual Western Protective Relay Conference, Spokane, WA, October 2007.

[17] D. Costello, M. Moon, and G. Bow, "Use of Directional Elements at the Utility-Industrial Interface," proceedings of the 5th Annual Power Systems Conference, Clemson, SC, March 2006.

[18] D. Costello and K. Behrendt, "Enabling Sensitive Directional Tripping for Non-Line Protection Applications With SEL-351 Series Relays," SEL Application Guide 2009-17. Available: http://www.selinc.com.

[19] NERC System Protection and Control Committee, "Protection System Reliability, Redundancy of Protection System Elements." Available: http://www.nerc.com/docs/standards/sar/Project2009-07_Tech_Paper_Reliability_of_Protection_Systems_2009Jan20.pdf.

VII. Biographies

Karl Zimmerman is a senior power engineer with Schweitzer Engineering Laboratories, Inc. in Fairview Heights, Illinois. His work includes providing application and product support and technical training for protective relay users. He is an active member of the IEEE Power System Relaying Committee and chairman of the Task Force on Distance Element Performance with Non-Sinusoidal Inputs. Karl received his BSEE degree at the University of Illinois at Urbana-Champaign and has over 20 years of experience in the area of system protection. He is a past speaker at many technical conferences and has authored over 20 papers and application guides on protective relaying.

David Costello graduated from Texas A&M University in 1991 with a BSEE. He worked as a system protection engineer at Central Power and Light and Central and Southwest Services in Texas and Oklahoma. He has served on the System Protection Task Force for ERCOT. In 1996, David joined Schweitzer Engineering Laboratories, Inc., where he has served as a field application engineer and regional service manager. He presently holds the title of senior application engineer and works in Boerne, Texas. He is a senior member of IEEE, a member of the planning committee for the Conference for Protective Relay Engineers at Texas A&M University, and a recipient of the 2008 Walter A. Elmore Best Paper Award from the Georgia Institute of Technology Protective Relaying Conference.

Previously presented at the 2010 Texas A&M
Conference for Protective Relay Engineers.

20101025 • TP6415-01