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Phase Selection for Single-Pole Tripping:

Weak Infeed Conditions and Cross-Country Faults

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PHASE SELECTION FOR SINGLE-POLE TRIPPING – WEAK INFEED CONDITIONS AND CROSS-COUNTRY FAULTS

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1. Introduction

Accurate fault type identification (or phase selection) is imperative for correct functioning of line relaying, particularly in Extra High Voltage (EHV) networks. The major applications for phase selecting schemes/algorithms include:

- Supervision of single-pole tripping/autoreclosing functions by distinguishing between single-line-to-ground and multi-phase faults and providing fast and correct identification of the faulted phase.
- Blocking specific distance elements during some faults because of the danger of limited accuracy of those elements (phase-to-ground distance elements during double-line-to-ground faults, for example).
- Providing correct fault type identification for an internal fault locator.
- Providing correct fault type identification for targeting and fault reporting.

It is well known that protection elements such as distance or phase-overcurrent may fail to provide accurate phase indication for particular line faults for the reasons outlined below:

First, when a fault occurs those elements that respond most quickly may not correctly identify the fault type. This could be resolved by delaying a trip output, but this is undesirable.

Second, protection elements can exhibit an inadvertent operation due to weaknesses in their specific design. For example, some phase distance elements may malfunction on close-in single-line-to-ground faults.

Third, some protection elements – such as the negative-sequence or zero-sequence directional overcurrent – can be programmed to trip the line but they lack the ability of identifying the fault type.

All the above call for fast and reliable phase selection schemes/algorithms.

This paper focuses on two challenging issues related to phase selection. They are weak-infeed conditions and cross-country faults.

In the case of a weak infeed, the fault currents can be very low. In fact, the currents may drop below the pre-fault load level for a fault on the line. In addition, wye-connected transformers installed in the adjacent substation or in near vicinity may generate significant zero-sequence infeed. If this happens, the asymmetry in the phase currents that is a signature of the fault type is buried beneath the dominating zero sequence current. The phase currents can be almost identical and reliable phase selection based exclusively on the current signals becomes extremely difficult.

In the case of a cross-country fault (F-1 and F-2 in Fig.1) – or more generally – any two or more simultaneous faults at different electrical locations (F-1 and F-3 in Fig.1), reliable phase selection is a problem as well. If the two faults are forward to a given relay considering the flow of the fault currents (F-1 and F-2 for Relay-2 in Fig.1), phase selectors would likely see a sum of all the phases included in the two faults as involved in the “seen fault”. If one of the two faults is reverse while the other is forward to a given relay

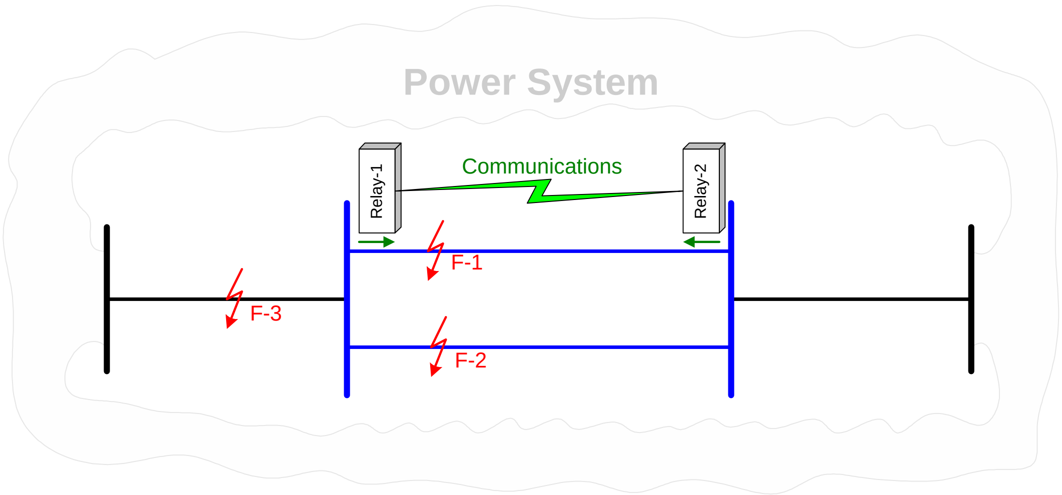

Figure 1. Parallel line arrangement.

(F-1 and F-2 for Relay-1 in Fig.1), phase selectors would tend either to see the electrically closer fault, see both as a single fault type, or see none of the known fault patterns.

The paper presents a new algorithm for fast and reliable phase selection. The algorithm combines the following pieces of information:

(a) Relation between the pre-fault and fault currents.

(b) Relation between the magnitudes of the positive-, negative- and zero-sequence currents.

(c) Relation between the phase angles between the negative- and positive-sequence currents with selected parameters being adaptable depending on the magnitude of the zero sequence current.

(d) Relation between the phase angles between the negative- and zero-sequence currents with selected parameters being adaptable depending on the magnitude of the zero sequence current.

(e) Relations analogous to (a) – (d), but for the voltages.

(f) Relation between the phase angles of the negative-sequence current and voltage.

Using the above information the new phase selector is capable of either recognizing the correct fault type or indicating its inability to do so. In the latter case, the phase selector uses indication provided by selected protection elements for fault type identification.

The paper discusses an issue of pilot protection during cross-country faults. The solution presented requires a communications channel capable of carrying more than one bit but is capable of single-pole tripping in weak-infeed conditions and during cross-country faults providing that at least one relay identifies the fault type correctly.

2. New Phase Selecting Algorithm

2.1. Overview of the Principle

Various approaches are used for fault type identification ranging from simple phase overcurrent checks to methods based on transient and superimposed signal components.

One family of methods uses relationships between the positive- and negative-sequence components of the fault current. Fig.2a illustrates the approach by showing the angular relationships between the positive- and negative-sequence fault currents. **(**The figure is valid for the ABC phase rotation and the sequence currents are referenced to phase A. A mirror image obtained by switching the B and C phases holds true for the ACB phase rotation.**)** The ten fault types (AG, BG, CG, AB, BC, CA, ABG, BCG and CAG) correspond to their angular positions being 60 degrees apart.

As seen from the figure, this method is not capable of distinguishing between line-to-line and double-line-to-ground faults. The zero sequence current can be used as a criterion. This is of a secondary importance, however, as the single-pole-tripping functions (always) and the fault locator (typically) act in the same manner regardless of the involvement of ground in multi-phase faults.

Another fault signature can be extracted from the relations between the negative- and zero-sequence currents as shown in Fig.2b. This approach alone cannot, however, be used for complete phase selection. First, the zero sequence current is not present during line-to-line faults. Second, the single-line-to-ground pattern (AG, for example) overlaps with the line-to-line-to-ground pattern involving the remaining phases (BCG, respectively). As drastically different functions are performed by a relay in the case of, say, the AG fault as compared to the BCG fault, this principle needs enhancements. One of the solutions is to check the angular position of the line-to-line (BC) voltage when recognizing a single-line-to-ground (AG) fault.

Both the approaches (negative-sequence versus positive-sequence – Fig.2a, and negative-sequence versus zero-sequence – Fig.2b) lack the ability of recognizing a symmetri-

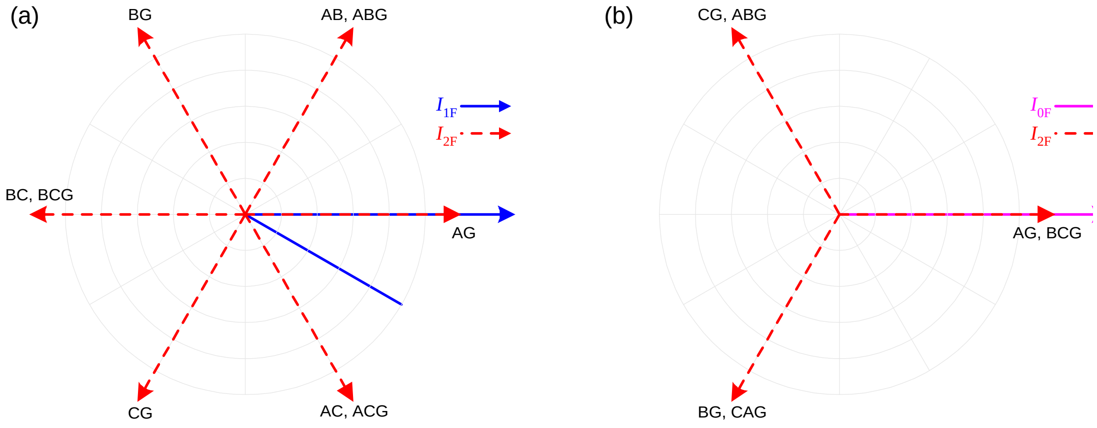

Figure 2. Negative-sequence vs. positive-sequence fault signature (a) and negative-sequence vs. zero-sequence fault signature (b). Valid for the ABC phase rotation.

cal three-phase fault. Significant positive-sequence current in the absence of both the negative- and zero-sequence currents can verify the three-phase fault selection.

Other important implementation aspects include the following:

- It is imperative to use only the fault components of the currents. This is easily accomplished by subtracting the pre-fault load values.
- Level checks should be applied to the negative- and zero-sequence currents prior to using their phase information to verify that these quantities are above the noise floor (three-phase and line-to-line faults).

The phase selection method based on the current sequence quantities has several advantages:

- The angular relations between the sequence quantities are very consistent. Factors such as fault current level, fault resistance, system and line impedances, etc. have almost no influence on the fault signatures shown in Fig.2.
- The method is based on phasors and as such can be efficiently implemented in digital relays because it does not require any extra calculations besides measurements already required for the basic protection functions.
- The method is naturally fast. This results from the fact that the phase angle of a phasor developing from zero to a finite magnitude is established very quickly – far before the data window of the phasor estimators gets filled with the fault data. Fig.3 illustrates this important advantage: it takes a comparatively long time for the positive sequence current to change its angular position between the pre-fault and fault states as its magnitude does not change significantly. In contrast, it takes a very short time to establish the correct angle position for the zero- and negative-sequence currents, as well as for the fault component of the positive-sequence current because these quantities develop from zero. With reference to Fig.3, for example, the expected angle difference of 120 degrees between the negative- and zero-sequence currents (CG fault shown) develops with sufficient accuracy as quickly as 4 msec after the fault inception despite the fact that the full-cycle algorithm has been used for phasor estimation.

The two major weaknesses of the approach are related to:

- Cross-country faults: two simultaneous faults at two different electrical locations, where, in addition, one of the faults could be in the forward and the other in the reverse direction, may confuse the phase selector.
- Weak- and/or zero-sequence infeed conditions: zero-sequence current dominating in the phase currents overshadows the fault signature making the identification impossible.

The new phase selecting algorithm solves the cross-country fault and weak-infeed condition problems by utilizing the voltage signal and applying adaptive techniques.

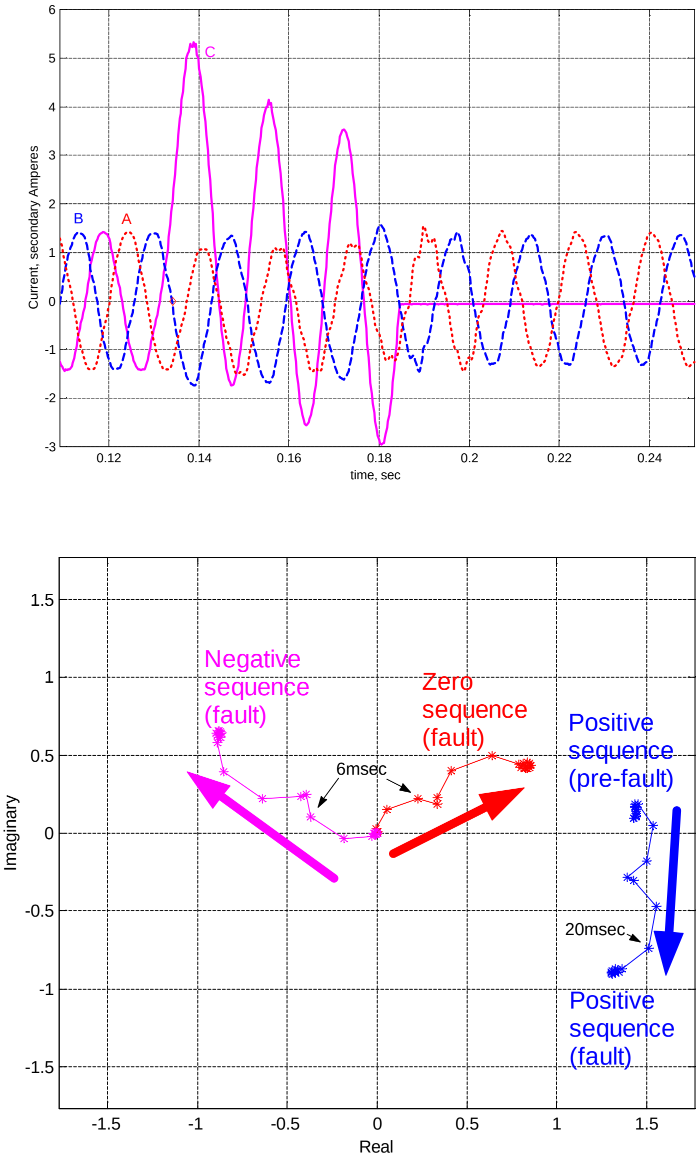

Figure 3. Illustration of measurement speed for phase angle of symmetrical currents – CG fault with heavy pre-fault load current (top) and development of the symmetrical current phasors (bottom - the asterisks stand for “protection passes” being 2 msec apart).

2.2. Block Diagram

With reference to Fig.4 the new algorithm uses both the current and voltage signals. The algorithm is organized in a hierarchical manner with the priority given to currents.

If voltages are not available the algorithm can operate using currents only.

If voltages are available, they are used only when information contained in currents is not sufficient to identify the fault type.

The currents are pre-filtered to remove the dc offset and converted into phasors. Subsequently the sequence quantities are calculated. A fault detecting procedure is required

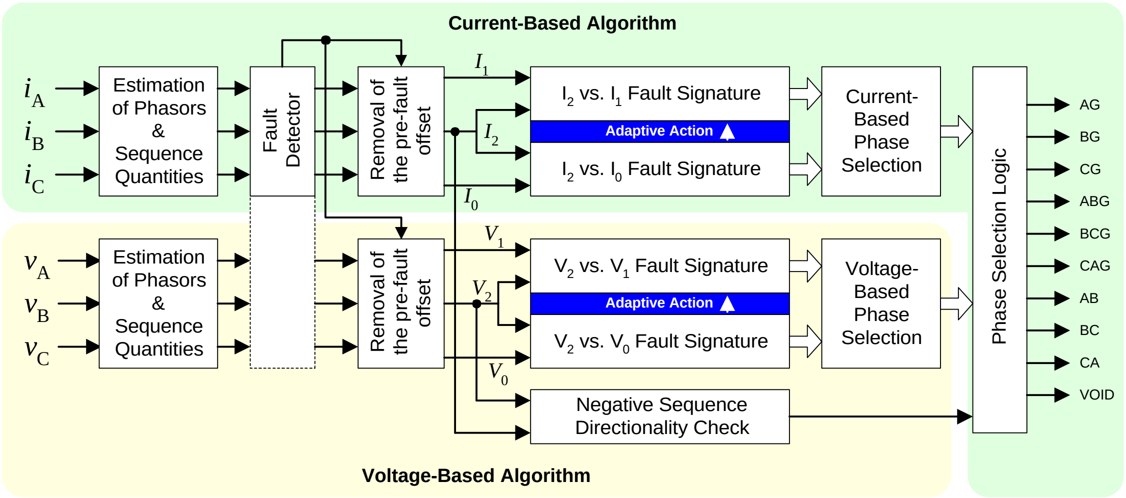

Figure 4. Overall block diagram of the Phase Selector.

to store the pre-fault values and subtract them from the measured currents. This operation applies to all positive-, negative- and zero-sequence currents. The removal is crucial for the positive-sequence current, but is also beneficial for the two other quantities if considerable load unbalance is present.

In the next step the magnitudes of the sequence currents are checked to decide whether the quantities have been established and their angular information can be safely utilized. This operation is performed using adaptive thresholds without the need for user entered settings.

If the negative- and zero-sequence quantities exist, the fault signature shown in Fig.2b is exploited (section 3). At the same time, the signature shown in Fig.2a are adaptively changed for faster operation (section 4).

The current-based path identifies a given fault type if the negative-sequence vs. positive-sequence (Fig.2a) and the negative-sequence vs. zero-sequence (Fig.2b) fault signatures match. In addition, if the voltage signal is available, the negative-sequence directional supervision is applied.

If this part of the algorithm fails to identify the fault type and the voltage signals are available, the voltage checks are performed in the identical manner as for the currents.

If after this, no consistent fault type is found, the VOID phase selection flag is set as described in section 5.

3. Exploited Fault Type Signatures

The method outlined in Fig.2 can be implemented in a number of ways.

One approach, for example, uses magnitude of the sum of the negative- and positive-sequence currents.

The method described in this paper directly checks the angular relationships between the sequence quantities according to the principle pictured in Fig.2. By using the phase angle information alone, the recognition is made more robust and faster. Additionally, this allows for the application of adaptive techniques.

With reference to Fig.5 six symmetrical "bells" are established to enclose the characteristic positions of the negative-sequence current with the positive-sequence current as reference (Fig.5a), and three "bells" to enclose the characteristic positions of the negative-sequence current with the zero-sequence current as reference (Fig.5b).

The maximum limit angle for the negative-to-positive-sequence check is 0.5•60 degrees = 30 degrees; for the negative-to-positive-sequence check the maximum limit is 0.5•120 degrees = 60 degrees. Practically, the limit angles should be smaller than 30 and 60 degrees, respectively. Smaller limit angles increase precision of fault type identification, but slow down the algorithm and create the danger of failure to operate as a given fault may not fall into any of the angle "bells" due to some angle abnormalities (series-compensation, for example).

The presented algorithm checks consistency between the recognition according to Fig.5a and Fig.5b. If the solution is consistent, it becomes the final fault type identified. If not, the algorithm uses the voltages.

The voltage part is identical to the current-based algorithm. The same relations (Fig.2) hold true for voltages. The only difference is the adaptive level check for sequence voltages and different values of limit angles.

If only the line-to-line voltages are available, the check shown in Fig.5b cannot be applied because the zero-sequence voltage cannot be estimated and the fault signature shown in Fig.5a is applied only.

If the voltage-based fault type recognition is consistent, it becomes the final fault type identified. If not, the VOID flag is set and the algorithm reports its inability to provide reliable fault type identification.

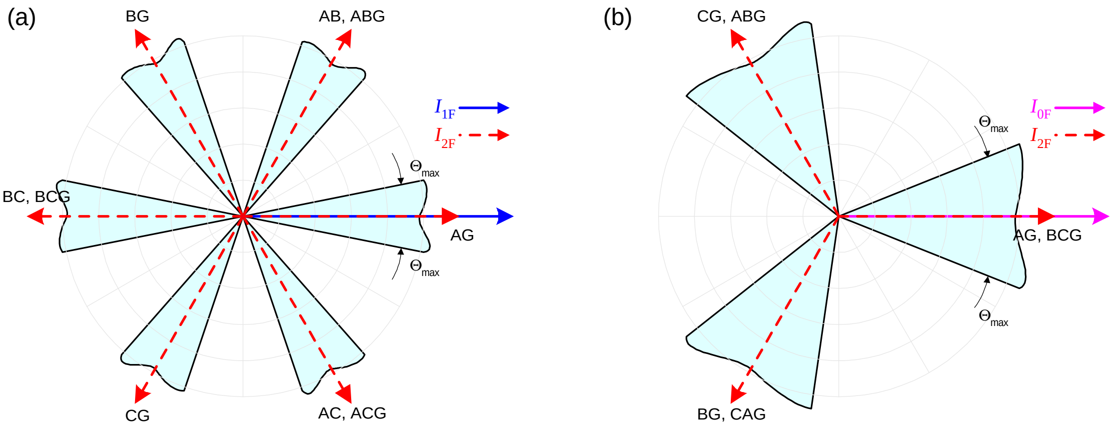

Figure 5. Illustration of the angle comparator limits: negative-sequence vs. positive-sequence fault signature (a) and negative-sequence vs. zero-sequence fault signature (b).

4. Adaptivity and Increased Security

The advantage of using two fault signatures simultaneously (Fig.2a and 2b) allows for relaxing the requirement for the maximum limit angle. The “bells” for either negative-to-positive-sequence or negative-to-zero-sequence (but not both) can overlap and correct fault type identification is still possible.

Widening the angle limit makes the recognition faster.

Fig.7 explains the idea. The limit angle for the negative-to-positive-sequence fault signature is wider than 30 degrees. Consequently, the developing negative- and positive-sequence phasors would earlier satisfy the conditions and speed-up the operation. During transients, however, two fault types could be indicated as shown in the figure (BG or ABG?). On the negative-to-zero-sequence plane, the two faults (BG and ABG) are 120 degrees apart enabling secure and fast recognition of the fault as BG.

The extra information from the negative-to-zero-sequence plane is not, however, guaranteed. During three-phase and line-to-line faults the zero-sequence current does not appear making the comparison of Fig.2b impossible. If this is the case, the limit angle should be reduced for the negative-to-positive-sequence plane to a safe value as shown in Fig.7.

It is also worth noting that the presented algorithm applies different (optimized) limit angles for:

- Single-line-to-ground faults (AG, BG, CG) and multi-phase faults (AB/ABG, BC/BCG, CA/CAG).
- Voltages and currents.
- Negative-to-positive-sequence and negative-to-zero-sequence planes.

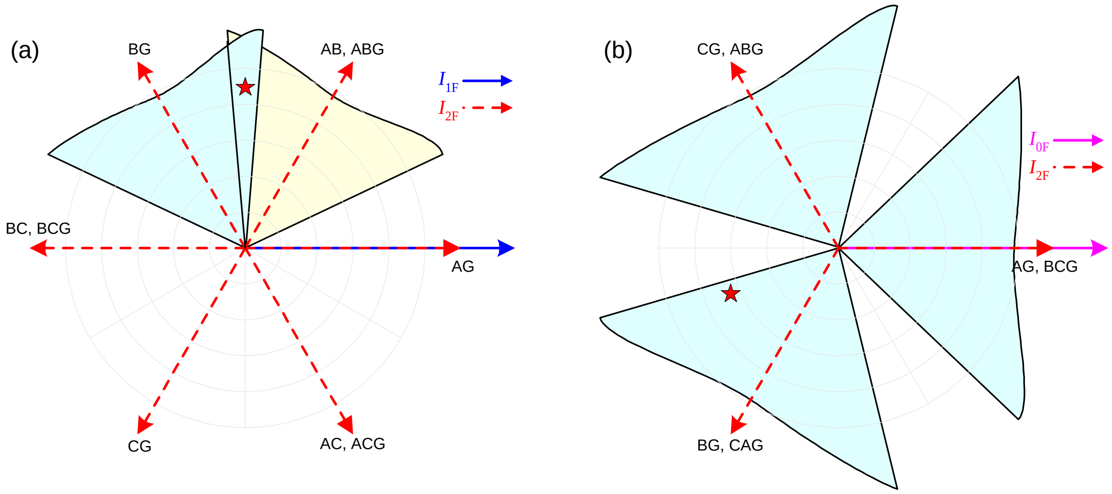

Figure 6. Owing to the negative-sequence vs. zero-sequence fault signature (b) operate regions for the negative-sequence vs. positive-sequence angle check may overlap (a). The asterisks indicate position of the negative-sequence current.

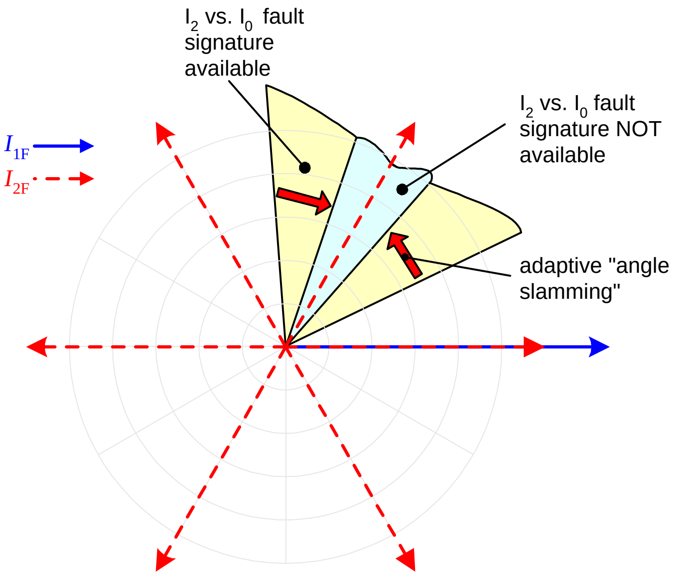

Figure 7. Illustration of the adaptive angle slamming for the negative-sequence vs. positive-sequence angle check.

5. VOID Fault Type Identification Instead of Maloperation

A choice has been made to include the "VOID" flag indicating that the phase selector is not capable of making secure fault type identification.

The flag is produced if:

A. Currents-only version:

- Both negative-to-zero-sequence and negative-to-positive-sequence fault signatures are not consistent, or
- Only negative-to-positive-sequence fault signature is available but the recognition cannot be made because the negative-sequence current does not fall into any of the angle "bells".

B. Currents and Voltages version:

- The negative-sequence directionality check fails to identify the fault as being in the forward direction, or
- The current part fails and both negative-to-zero-sequence and negative-to-positive-sequence fault signatures are available for voltages but the recognition is not consistent, or
- The current part fails and only negative-to-positive-sequence fault signature is available for voltages but the recognition cannot be made because the negative-sequence voltage does not fall into any of the angle "bells".

The flag requires the relay to use protection elements (such as distance) for phase selection.

6. Examples

6.1. Cross-Country Fault Example

Figs.8 and 9 show voltages and currents, respectively for Relay-2 of Fig.1 during a sample cross-country fault. The first fault (AG at F-1 location) occurs on the protected line at 99% of the line length from Relay-2. Ten milliseconds later the second fault (CG at F-2 location) occurs on the parallel line at the same geometrical location.

Fig.10 presents the key outputs from the phase selector. The first fault (AG) is recognized in 2.6 msec. The second fault is almost at the same electrical location as seen by the Relay-2. Therefore, as the second fault occurs the phase selector changes its output to CAG.

In order to distinguish between the two faults, Relay-2 would have to be capable of distance discrimination with enormous accuracy. This is not practical. As shown in section 7, correct single-pole tripping action can be accomplished by a pilot scheme providing Relay-1 identifies the fault correctly.

Fig.10 illustrates also the tracking abilities of the fault selector. If a fault evolves, the phase selector will follow its type. New phases getting involved in the fault generate extra transients and uncertainty. The phase selector responds to that by setting the VOID flag for a short period of time rather than providing wrong identification.

Figs.11 and 12 show voltages and currents, respectively for Relay-1 of Fig.1 for the same fault. For Relay-1 the first fault is a forward fault located 1% from the substation, while the second fault is a reverse fault.

Fig.13 presents the key outputs from the phase selector for Relay-1. Owing to the increased security, the phase selector is capable of “ignoring” the second fault and providing correct fault identification.

Figs.10 and 13 illustrate also the need for disabling the algorithm during breaker operation and autoreclosure dead time. During and after the breaker operation, the fault disappears and the phase selector traces a new pattern resulting from open breaker poles.

6.2. Weak- and Zero-Sequence Infeed Example

Figs.14 and 15 show voltages and currents, respectively for Relay-2 of Fig.1 for the BCG fault (F-1 location at 50% of the line) under weak-infeed conditions.

As seen in Fig.15, the zero-sequence component dominates the currents. Consequently, all three-phase currents are in phase and of the same magnitude level not much different from the pre-fault load. A simple overcurrent check for phase selection will certainly fail in this case.

The voltage signals are heavily distorted (Fig.14), but they convey enough information to correctly identify the fault type.

As shown in Fig.16 the algorithm is slower and requires one cycle to declare the BCG fault, but the relay is not likely to be ready to trip by that time because of the weak infeed. It is also worth noticing that the VOID flag is kept prior to that and no false indication is given before the algorithm reaches enough consistency to identify the fault.

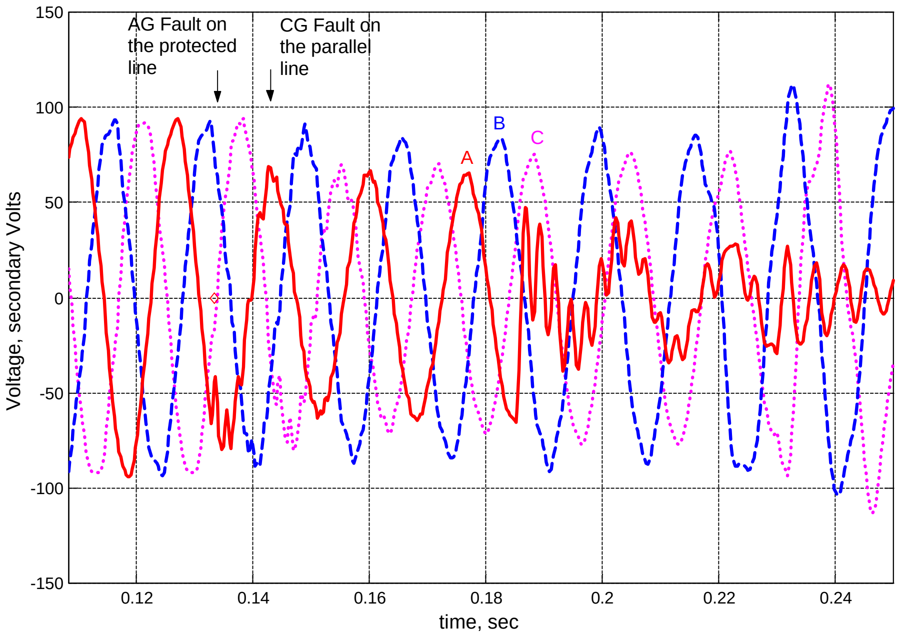

Figure 8. Cross-country fault example. Relay 2 – Voltages.

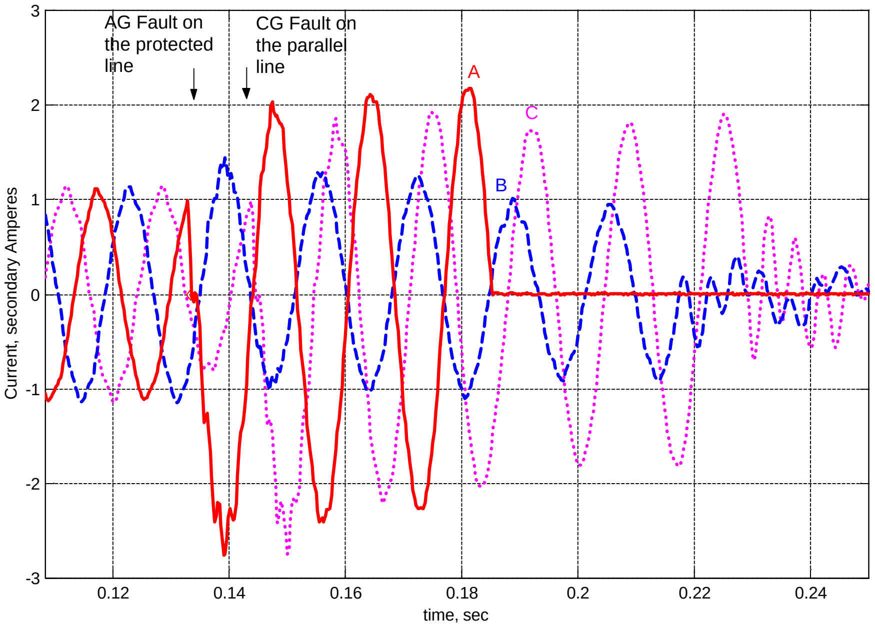

Figure 9. Cross-country fault example. Relay 2 – Currents.

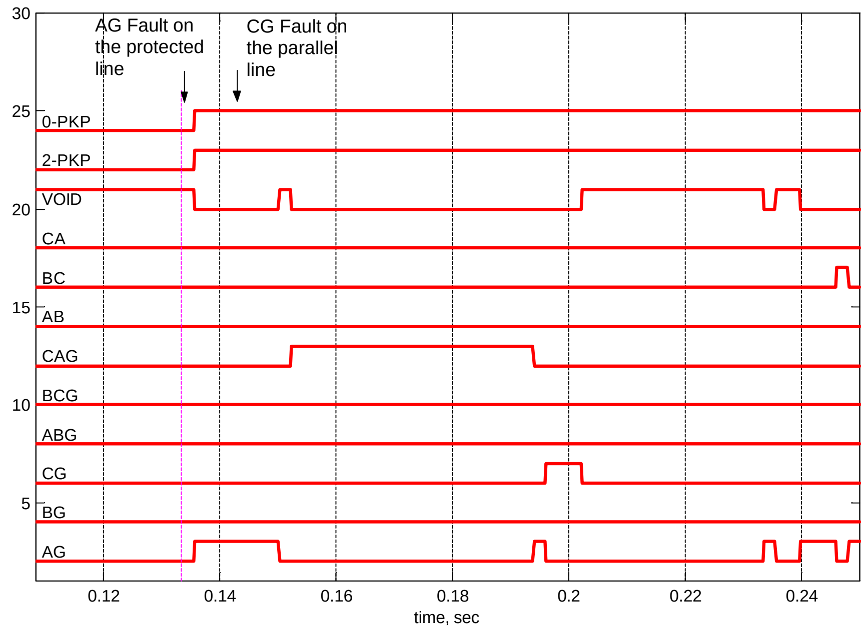

Figure 10. Cross-country fault example. Relay 2 – Phase Selector flags.

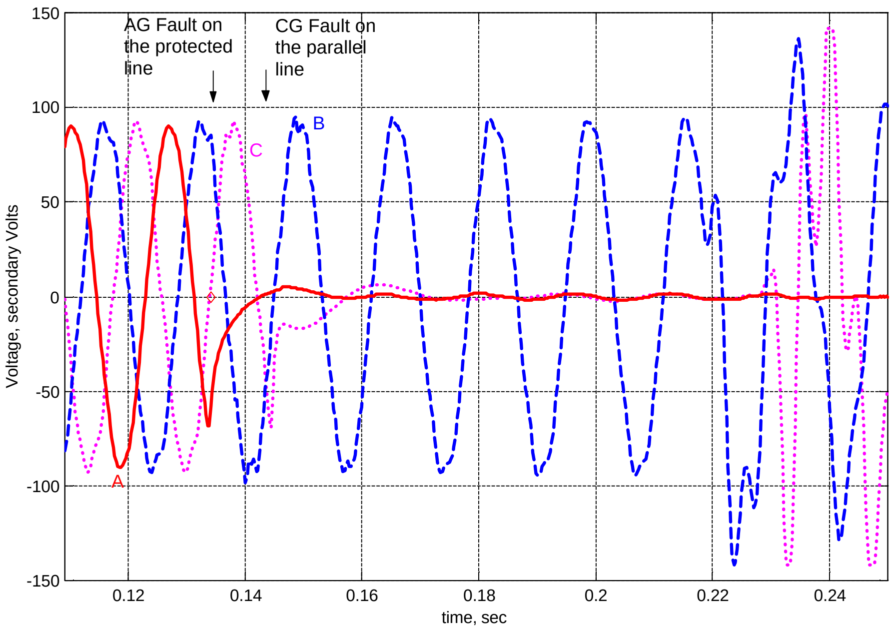

Figure 11. Cross-country fault example. Relay 1 – Voltages.

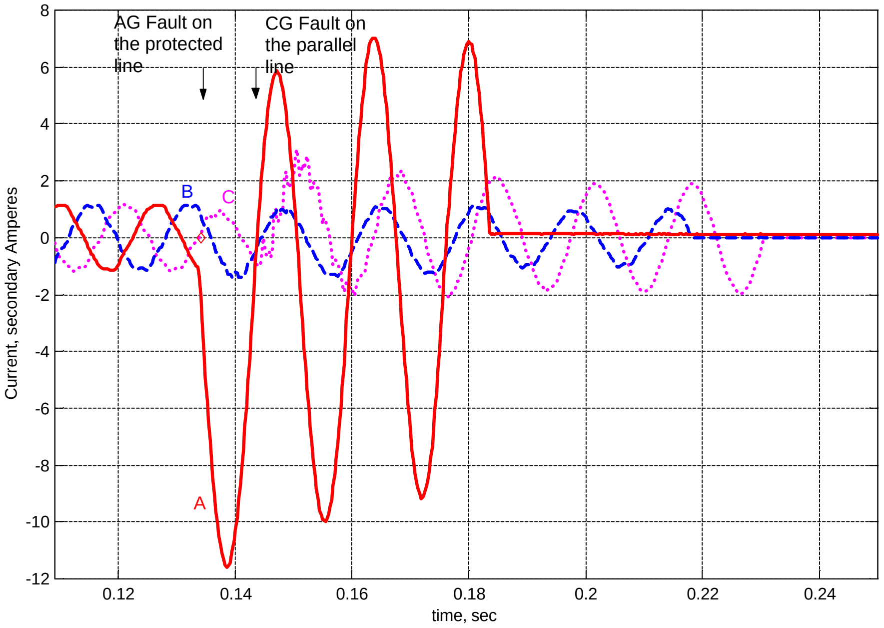

Figure 12. Cross-country fault example. Relay 1 – Currents.

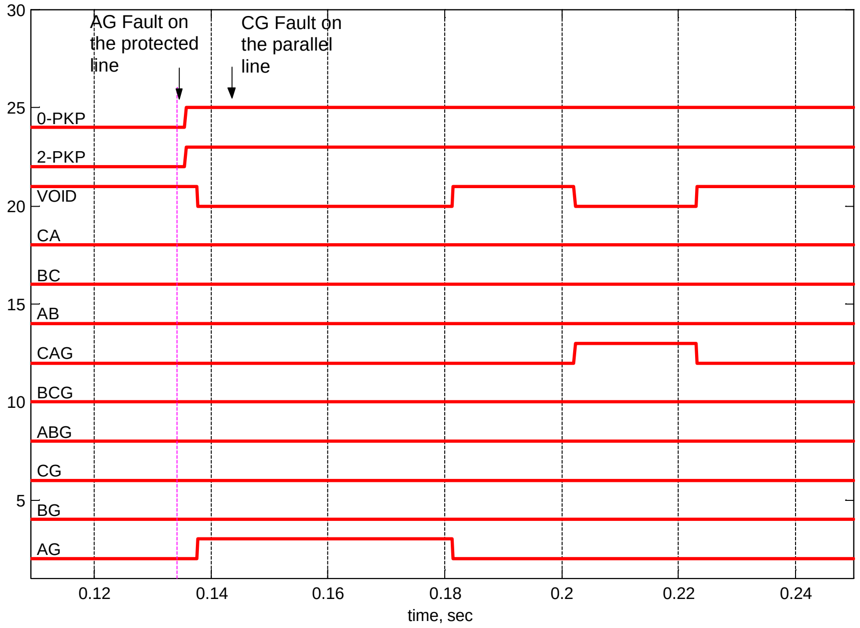

Figure 13. Cross-country fault example. Relay 1 – Phase Selector flags.

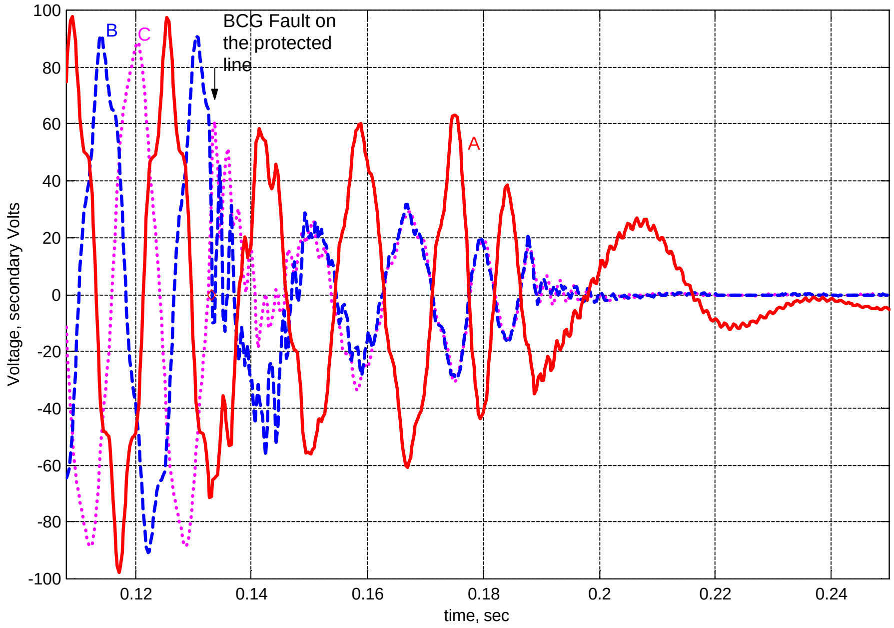

Figure 14. Weak-infeed example – Voltages.

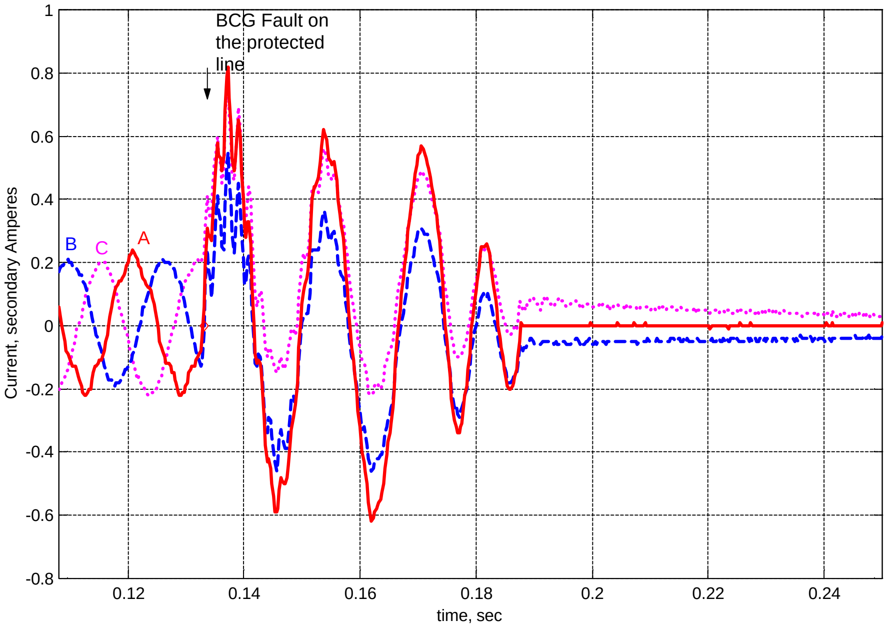

Figure 15. Weak-infeed example – Currents.

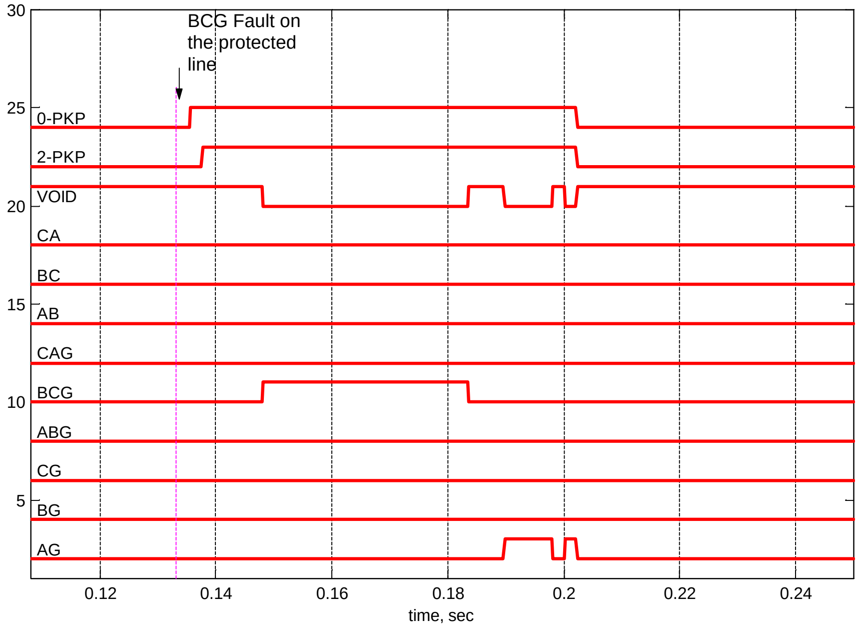

Figure 16. Weak-infeed example – Phase Selector flags.

7. Pilot Schemes

With reference to Fig.1 Relay-2 alone is not able – regardless of the applied principle for phase selection – to identify a cross-country fault involving the F-1 and F-2 locations. Consider for example, the AG fault on the protected line “a few feet” from Relay-1 and the BG fault “a few feet” backwards on the parallel line. Electrically, from the position of Relay-2 this IS a double-line-to-ground (ABG) fault.

Ultimately, as the two faults are closer, the signals at the Relay-2 location will become similar making the two cases (cross-country fault (AG+BG) and double-line-to-ground fault (ABG)) unrecognizable.

Certainly, for some cross-country faults, the selection may be correct, but generally, accurate phase identification by separate protective relays cannot be guaranteed. Pilot schemes offer a chance for more reliable phase selection for the critical task of single-pole tripping.

7.1. Single-Channel Schemes

The situation is not better for a pilot scheme with a single communication channel (single bit of information exchanged).

Analyze, for example, the Permissive Overreaching Transfer Trip (POTT) scheme. The bit of information that is exchanged bears the meaning “fault in forward direction” and cannot accommodate any extra information that would help to improve phase selection. The fault type identification must be entirely performed locally by the two relays.

Consider the example presented is subsection 6.1. Relay-1 would initiate single-pole tripping / autoreclosing action in phase A (correct); Relay-2 in turn would initiate three pole trip (incorrect). This situation cannot be resolved by using protection elements for phase selection. By principle of the POTT scheme, the channel is keyed by an overreaching element (overreaching distance zone or directional overcurrent element) that would see the fault on the parallel line and recognize the situation as the CAG fault.

7.2. Two-Channel Schemes

The problem can be addressed successfully if at least two bits of information are exchanged between the relays. Two bits are capable of encoding four different states. Obviously the “fault is/is not in the forward direction” is one of the four states. Owing to some specific symmetries between various fault types, the three remaining states are capable of improving phase selection considerably.

One particular solution (Fig.17) applies the “Transmit Logic” shown in Table 1, and the “Trip Logic” shown in Table 2.

Consider the example presented is subsection 6.1:

- Relay-2 identifies the CAG fault and transmits the word of 01 (Table 1).
- Relay-1 identifies the AG fault and transmits the 10 (table 1). Having the 01 received, Relay-1 initiates single-pole trip in phase A (table 2).
- Having the 10 received, Relay-2 initiates single-pole trip in phase A (table 2).

Both relays initiated correct single-pole tripping despite wrong local phase selection by Relay-2.

The presented phase selector algorithm recognizes its inability to perform a correct phase selection, i.e. it will rather set the VOID flag than provide a wrong phase selection.

Consider again the example 6.1. If the two faults are further from Relay-1, the phase selector will get confused and will set the VOID flag. If this is the case, Relay-1 will switch to distance elements for phase selection (Fig.17). In this particular case, the distance elements will operate correctly, i.e. the AG element will pick-up; while the CG element will not. This resolves the situation and single-pole trip will be initiated at both ends of the line.

The presented solution addresses the most likely phase selection “mistakes” such as two single-line-to-ground faults seen as one double-line-to-ground fault.

Table 1. Transmit Logic for Two-Channel Scheme.

Fault Type (Local)	Tx1	Tx2	Transmitted Word
AG, BC, BCG	Key		10
BG, CA, CAG		Key	01
CG, AB, ABG, 3P	key	Key	11

Table 2. Trip Logic for Two-Channel Scheme.

Received Word	Fault Type (Local)	Trip Action
01	AG	TRIP A
11		
10	AG	
	AB, ABG, 3P	
	CA, CAG	
10	BG	TRIP B
11		
01	BG	
	AB, ABG, 3P	
	BC, BCG	
10	CG	TRIP C
01		
11	CG	
	BC, BCG	
	CA, CAG	
11	AB, ABG, 3P	TRIP 3P
10	BC, BCG	
01	CA, CAG	

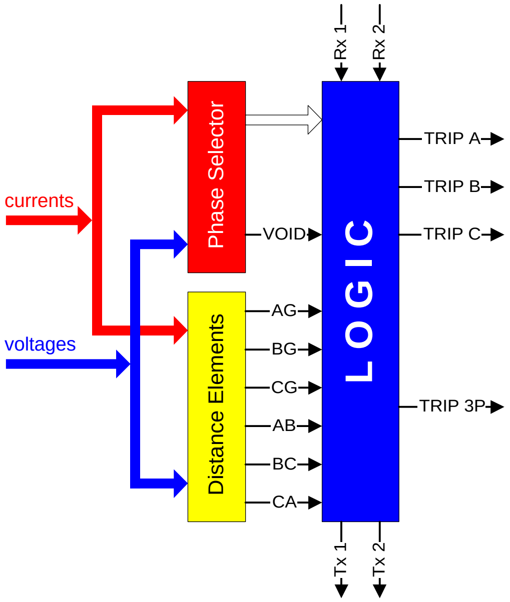

Figure 17. Usage of the Phase Selector and Distance elements for single-pole tripping mode with two communication channels.

8. Conclusions

The issues of cross-country faults and weak infeed conditions have been discussed in conjunction with phase selection and single-pole tripping/autoreclosing functions.

A new phase selection algorithm has been presented that uses a proven principle enhanced by the novel usage of voltage signals and adaptive techniques.

The idea of “self-monitoring” has been applied to the phase selector. The algorithm sets the VOID flag in uncertain situations instead of providing wrong information. The uncertain situations for the applied algorithm are likely to be resolved by distance elements. Such hierarchical combination of the phase selector and the distance elements provides much better performance.

The phase selector can work using currents only, currents and line-to-line voltages, or currents and full set of voltages. The phase selector is fast and operates typically between ¼ and ½ of a power cycle.

The issue of single-pole tripping initiated by pilot schemes during cross-country faults has been discussed. A solution is presented which uses two channels to improve the performance in the single-pole tripping mode.

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The authors would like to acknowledge the assistance of Mr. Dave Sharples in the development of the concepts contained in this paper

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Biographies

Bogdan Kasztenny received his M.Sc. (89) and Ph.D. (92) degrees (both with honors) from the Wroclaw University of Technology (WUT), Poland. Dr.Kasztenny worked as an Assistant Professor at WUT and as a Visiting Assistant Professor at Southern Illinois University (SIU) and Texas A&M University (TAMU). From 1994 till 1997 he was involved in applied research for Asea Brown Boveri. He spent one year as a Senior Fulbright Fellow at TAMU. Currently, Dr.Kasztenny works for GE Power Management as a Senior Application/Invention Engineer. Dr.Kasztenny is a Senior Member of IEEE, holds several patents, and has published more than 100 technical papers.

Bruce Campbell graduated in Electrical Technology from the Northern Alberta Institute of Technology in 1964. He has been involved in the design, commissioning and startup of high voltage electrical equipment in North America, the Caribbean, Africa, the Middle East and Southeast Asia. He is presently the chief application engineer for GE Power Management, involved in conceptual and scheme design for digital protective relays, and consulting on power system protection. He is a member of PES of the IEEE.

Jeff Mazereeuw graduated in Electronic Engineering Technology from the DeVry Institute of Technology in 1987. Since then, he has been employed at GE Power Management. He has held various roles including product support and lead designer on several protective relay designs for motor, generator and power system applications. He is presently the New Product Introduction manager for GE Power Management. He is a member of the IEEE.

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