High-Speed Communication-Assisted Tripping and Sectionalizing for Distribution Systems

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Abstract -- The recent advent of Smart Grid has given rise to advances in communication systems for distribution systems. Modern numerical overcurrent relays have the technology available to utilize these communication channels for both high speed-assisted tripping and sectionalizing. Assisted tripping and sectionalizing allows the utility to operate their distribution system in a network as opposed to radial feeders. A networked system is much more reliable and customers experience fewer outages since there are multiple sources readily available. Assisted tripping and sectionalizing quickly isolates the fault and eliminates the need for long clearing times and complex coordination typically associated with classical time overcurrent protection.

This paper demonstrates how to apply communication-assisted tripping and sectionalizing, taking into account specific considerations for distribution systems not necessary for transmission applications—for example, a feeder with distributed generation connected. Several detailed examples are presented as to how to implement these schemes for typical distribution systems. This paper also gives specific settings and operational details of these schemes. Additionally, a review of the operational history highlights the impact that these schemes have on the reliability of the utility distribution network.

I. Introduction

This paper demonstrates how to perform high-speed communication-assisted tripping and sectionalizing on distribution systems. All faults are quickly cleared and the distribution system is rapidly sectionalized to restore service to the most customers possible. Inherent time delays embedded in the traditional approach are eliminated.

This paper is intended for portions of rural electric distribution systems that can operate in a network. This application is limited since the majority of rural electric distribution systems consist of long tapped radial feeders; however, there are instances when a portion of a system can be operated as a looped network. The main advantage of a network is less chance of customer outages when a primary source is lost—a very important for customers with critical needs such as hospitals.

The Smart Grid era has ushered in a new age revitalizing our distribution assets. The Smart Grid utilizes digital technology such as high-speed communication at the enterprise level. Many rural areas still lack DSL and cable modem services. In such cases, the least expensive type of non-dial-up connection remains a 64-kbit/s frame-relay line (Fig. 1). Smart Grid could provide rural electric utilities an incentive to loop their feeders to improve service. The paper provides a series of simple examples illustrating how to protected looped feeders since conventional protection such as time overcurrent relays alone are inadequate.

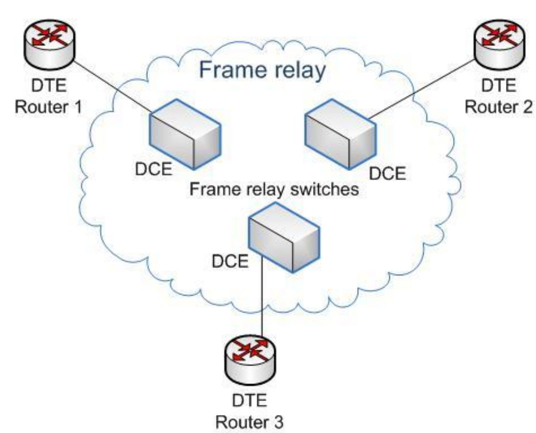

Fig. 1. Frame relay topology

II. High-Speed Communication-Assisted Tripping (HSCAT)

Fig. 2 illustrates two distribution feeders that are tied together by a section of feeder (length equal to d). The tie switch (S) is shown located beside the first feeder for the sake of practicality. The two substations must share a high-speed communications channel that allows the numerical line relays located at each terminal to transmit and receive data from each other. *The HSCAT scheme logic does not need to know the state of the tie switch.*

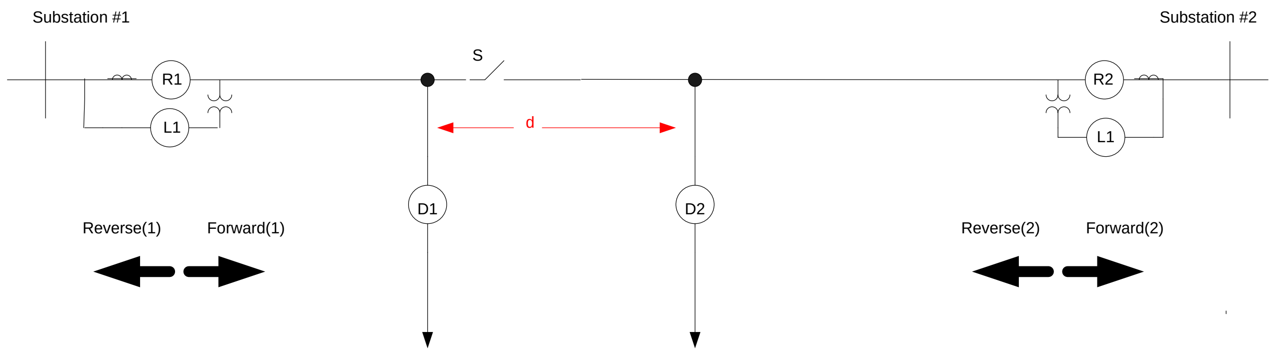

Fig 2. Single-line diagram for HSCAT scheme

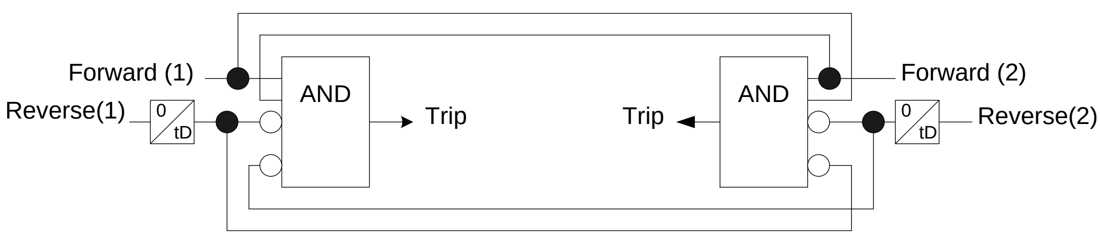

Fig 3. HSCAT scheme logic

Where:
R1 Recloser #1
R2 Recloser #2
L1 Feeder Relay #1
L2 Feeder Relay #2
D1 Sectionalizer #1 (motor operated - no remote control)
D2 Sectionalizer #2 (motor operated - no remote control)

The normal practice is to only close the tie switch when one of the reclosers is open to pick up the entire load on that feeder. HSCAT provides high-speed tripping at both ends via the communication channel for faults anywhere in-between when the tie switch is closed. *High-speed tripping the two reclosers eliminates the need for coordination between the reclosers with their perspective sectionalizers for the first trip*. Most faults are transient in nature (> 90%) and should have cleared prior to the first reclose. The next section of the paper discusses how to rapidly sectionalize the system to quickly restore service when the fault is permanent. Motor-operated sectionalizers cannot break current and trip after sensing the fault current has cleared.

Fig. 3 shows simple conceptual scheme logic for HSCAT. This is often referred to as a permissive overreaching transfer trip (POTT) scheme. Note that the VTs and CTs at each end must be connected such that both of the two numerical relays can distinguish between a feeder fault (forward) and an external fault located behind the terminal (reverse). Modern numerical feeder relays have directional elements that can determine if a fault is forward or reverse with respect to its own location.

- If a fault is between the two terminals and the tie switch is closed, then both numerical feeder relays declare a forward fault and trip their respective breakers after receiving permission from the remote end, quickly clearing the fault.

- If the tie switch is open, then one numerical line relay will not see the fault and the feeder protection reverts back to classic coordinated time overcurrent protection.
- If there is an out-of-section fault and the tie switch is closed, then one numerical relay sees the fault as reverse and blocks tripping at both terminals. If the reclosers are fed by delta/wye distribution transformers, then ground directional elements will not see single phase-to-ground faults on the interconnected transmission system.

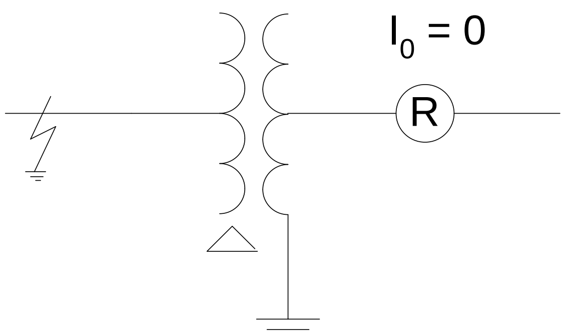

Fig 4. Ground faults on transmission system

III. High-Speed Sectionalizing for Permanent Faults

It was pointed out in the previous section that if the fault is permanent, then it is possible to rapidly sectionalize the distribution system and quickly restore service. *The tie switch must have a numerical control with access to the high-speed communications channel so that the numerical feeder relays can send remote trip and close commands.* Fig. 5 shows where faults can occur on the distribution system from our first example. This section covers the number of steps and what actions must be performed to properly isolate the fault for each location. We only need to cover the odd numbered fault locations due to the symmetry of the distribution system for this example. Note that once the tie switch is initially tripped open, the recloser and sectionalizer on the faulted segment rely upon traditional coordination to trip during the second step.

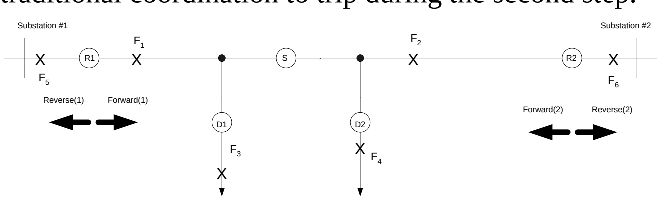

Fig. 5. Fault locations

<u>FAULT LOCATION F_1</u>

Step 1. Trip both reclosers R1 and R2 via HSCAT scheme.
Step 2. Trip the tie switch S.
Step 3. High-speed reclose reclosers R1 and R2.
Step 4. Trip and lockout recloser R1.

<u>FAULT LOCATION F_3</u>

Step 1. Trip both reclosers R1 and R2 via HSCAT scheme.
Step 2. Trip the tie switch S.
Step 3. High-speed reclose reclosers R1 and R2 (1st shot).
Step 4. Trip recloser R1.
Step 4. Trip and lockout sectionalizer D1.
Step 5. Reclose recloser R1 (2nd shot).

<u>FAULT LOCATION F_5</u>

The fault appears as external to the HSCAT scheme since the fault is reverse with respect to the numerical line relay at Substation No. 1 and forward with respect to the numerical feeder relay at Substation No. 2. The transformer differential protection can trip and lockout recloser R1 if the CTs are connected as shown in Fig. 6.

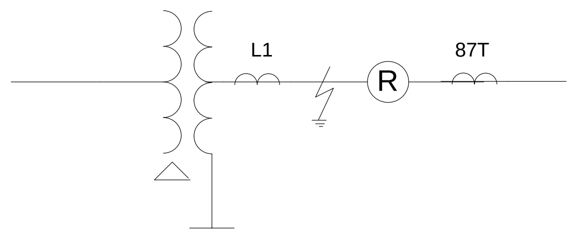

Fig 6. CT locations for bus faults

IV. Complex Distribution System

The distribution systems considered so far are very simple to help present the main concepts. Fig. 7 represents a more complex looped distribution system. We shall now analyze how to apply the HSCAT scheme logic for this system.

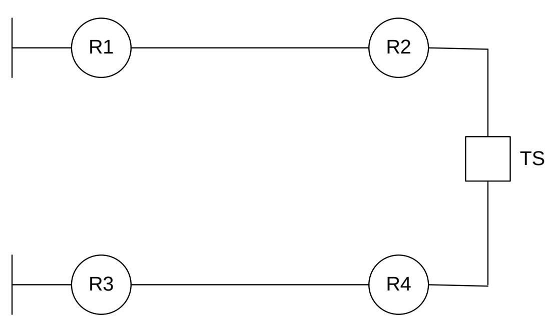

Fig 7. Looped distribution system

Reclosers R1 and R3 are located at the two substations while reclosers R2 and R4 are out in the system. TS is the normally closed tie switch. All of these devices must share the same high-speed communications channel that allows the numerical line relays located at each terminal (including the tie switch) to transmit and receive data from each other. Assume that the forward direction for reclosers R1 and R3 is looking out into the system while for reclosers R2 and R4 it is looking back towards their respective substations.

A. First Case – F_1

Fig. 8 illustrates a fault located between reclosers R1 and R2.

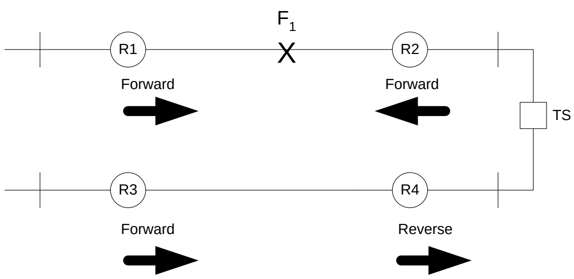

Fig. 8. Fault between reclosers R1 and R2

B. Second Case – F2

Fig. 9 illustrates a fault located between reclosers R3 and R4.

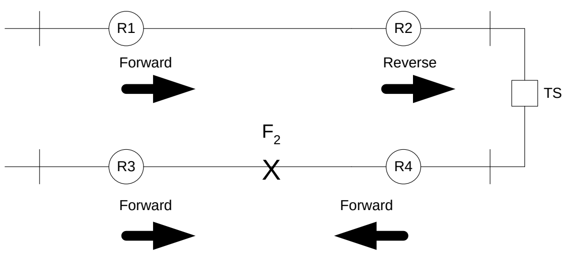

Fig. 9. Fault between reclosers R3 and R4

C. Third Case – F_3

Fig. 10 illustrates a fault located between reclosers R2 and R4.

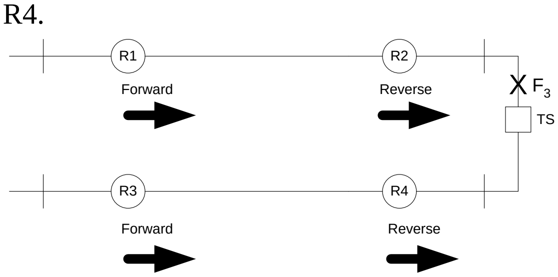

Fig 10. Fault between reclosers R2 and R4

D. Fourth Case – F_4

Fig. 11 illustrates a fault located behind R1.

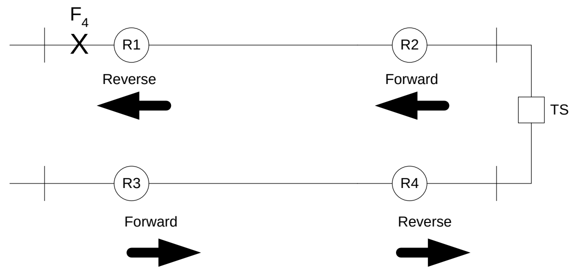

Fig. 11. Fault behind recloser R1

E. Fifth Case – F_5

Fig. 12 illustrates a fault located behind R3.

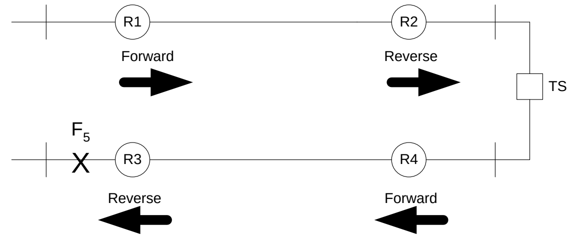

Fig. 12. Fault behind recloser R3

Table 1 shows the directional decisions made by the numerical feeder relays for each fault location.

TABLE 1.
RELAY DIRECTIONAL DECISIONS

FL/Relay	R1	R2	R3	R4	Result
F_1	F	F	F	R	Trip Zone 1
F_2	F	R	F	F	Trip Zone 2
F_3	F	R	F	R	Trip Zone 3
F_4	R	F	F	R	Block
F_5	F	R	R	F	Block

Fig. 13 shows how to apply HSCAT to protect the looped system:

- The numerical feeder relays at R1 and R2 provide the first zone of protection for the feeder between them; i.e., forward-looking directional elements
- The numerical feeder relays at R3 and R4 provide the second zone of protection for the feeder between them; i.e., forward-looking directional elements
- The numerical relays at R2 and R3 provide the final zone of protection for the feeder between them; i.e., reverse looking directional elements.

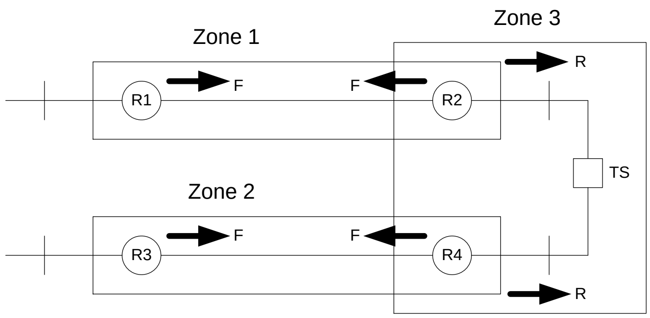

Fig. 13. Overlapping zones of protection

Therefore, the minimum requirements for point-to-point communications are as follows:

- R1 to R2 (if necessary R1 can transfer trip TS via R2)
- R3 to R4 (if necessary R3 can transfer trip TS via R4)
- R2 to TS
- R3 to TS

V. High-Speed Sectionalizing for Permanent Faults

Fig. 14 is the same looped system shown in Fig. 6 with sectionalizers included to better represent an actual system and shows all of the internal fault locations. If the fault is permanent, then it is possible to rapidly sectionalize the distribution system and quickly restore service. *The tie switch must have a numerical control with access to the high speed communications channel so that the numerical feeder relays can send remote trip and close commands.* Assume that the sectionalizers are motor operated and provide remote fault indication. This section covers the number of steps and what actions must be performed to properly isolate the fault for each location. Only the odd numbered fault locations need to be covered due to the symmetry of the distribution system for this example.

FAULT LOCATION F_1

Step 1. Trip both reclosers R1 and R2 via HSCAT scheme (*no fault indication from D1*).
Step 2. High speed reclose reclosers R1 and R2.
Step 3. Trip and lockout reclosers R1 and R2.

FAULT LOCATION F_3

Step 1. Trip both reclosers R1 and R2 via HSCAT scheme (*fault indication from D1*).
Step 2. High speed reclose reclosers R1 (1^{st} shot).
Step 3. Trip recloser R1.
Step 4. Trip and lockout sectionalizer D1.
Step 5. Reclose recloser R1 (2^{nd} shot).

FAULT LOCATION F_5

Step 1. Trip both reclosers R2 and R4 via HSCAT scheme (fault indication from D2).
Step 2. Trip open tie switch S.
Step 2. High speed reclose reclosers R2 and R4 (1st shot).
Step 3. Trip recloser R2.
Step 4. Trip and lockout sectionalizer D2.
Step 5. Reclose recloser R2 (2nd shot).

FAULT LOCATION F_7

Step 1. Trip both reclosers R2 and R4 via HSCAT scheme (no fault indication from D2 or D4).
Step 2. Trip open tie switch S.
Step 3. High speed reclose reclosers R2 and R4 (1st shot).
Step 4. Trip and lockout recloser R2.
Step 5. Reclose recloser R4 (2nd shot).

VI. Special Considerations

There are special conditions associated with operating a looped distribution system that must be taken into consideration:

- Ground sources
- Single pole tripping
- Directional element polarizing quantities

A. Ground Sources

Three-phase transformers out in the system that have a star-connected winding facing the distribution system can provide a ground path and back feed external faults tripped at one end of a looped feeder. The numerical feeder relay located at R1 in Fig. 15 should be able to identify the ground fault as external due to its directional elements.

B. Single Pole Tripping

Single pole tripping on distribution feeders has become popular in some areas such as Florida since many loads are single phase (i.e., residential). Tripping only the faulted phase during a single line-to-ground fault prevents interruption of service to single phase load connected to the unfaulted phases.

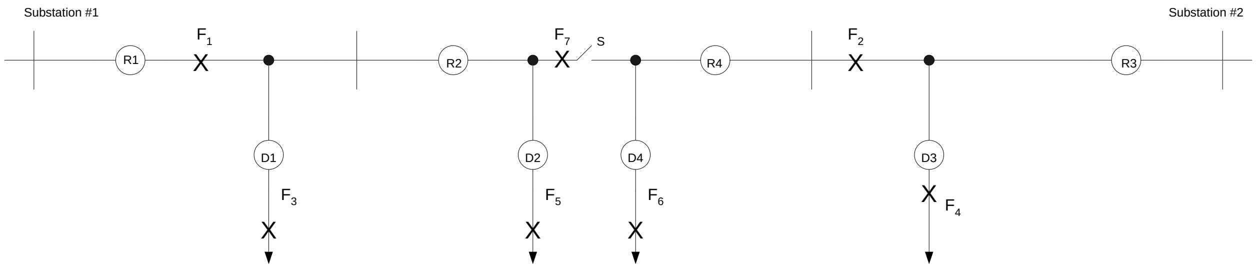

Fig. 14. Looped distribution system with sectionalizers

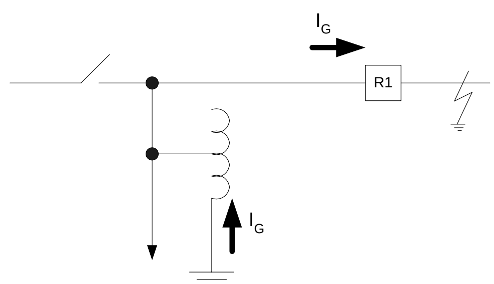

Fig. 15. Back-fed ground fault

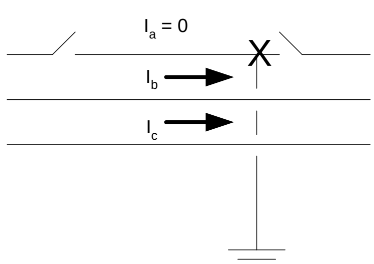

Fig. 16. A-phase tripped open

Negative-sequence and zero-sequence current flows through the unfaulted phases during the dead time following a single pole trip prior to reclosing.

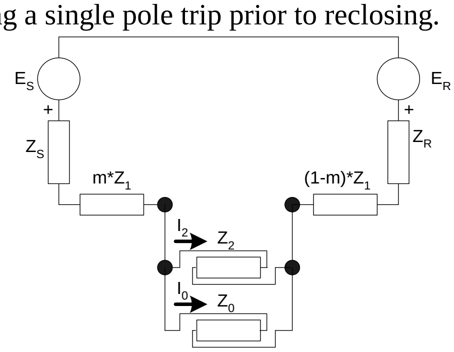

Fig. 17. Symmetrical component diagram for single-pole open

Fig. 17 is a symmetrical component diagram for one pole open on a looped distribution feeder. The unbalance current flows through the parallel combination of the negative-sequence and zero-sequence system impedances at the point where the open pole exists.

ES ≡ Equivalent Source at Substation S

ER ≡ Equivalent Source at Substation R

ZS ≡ Equivalent Source Impedance at Substation S

ZR ≡ Equivalent Source Impedance at Substation R

m ≡ distance to open pole from Substation S

Z1 ≡ Positive-Sequence Feeder Impedance

Z2 ≡ Negative-Sequence System Impedance

Z0 ≡ Zero-Sequence System Impedance

I2 ≡ Negative-Sequence Current

I0 ≡ Negative-Sequence Current

This condition can cause false operation of directional elements that are polarized by negative-sequence or zero-sequence quantities. Analysis is required to determine if the directional elements will work properly during the open pole and what actions, if any, must be taken to prevent misoperations from occurring.

C. Directional Element Polarizing Quantities

The choice of polarizing quantities is very important to ensure both reliability and security of the high-speed communication-assisted tripping scheme. Generally negative-sequence is chosen for unbalanced faults while positive-sequence is required for three-phase balanced faults. As pointed out in the previous section, caution should be exercised for the selection of the polarizing quantity for unbalanced faults when single pole tripping is enabled. *Negative-sequence and zero-sequence current due to the open pole actually flow backwards*. Fig. 18 shows the directional decision for a negative-sequence voltage polarized directional element during a forward fault. If I_2 is lagging $–V_2$ by 90 degrees, then the fault is declared forward.

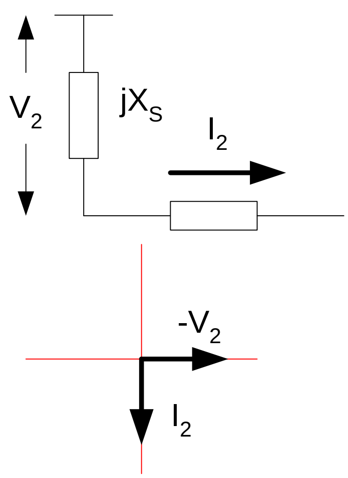

Fig. 18. Negative-sequence voltage polarized directional decision for forward fault (CCW rotation)

Forward Fault

$V_2 = -jX_S \bullet I_2$

$I_2 = -j|I_2|$

$V_2 = -X_S \bullet |I_2|$

The phase of the negative-sequence voltage is inverted for a reverse fault. So, for the case of reverse flow of the negative-sequence current during an open pole a negative-sequence voltage polarized directional element can still correctly determine the actual direction of the open pole with respect to the relay terminal as shown in Fig. 19. However, directional elements that operate on impedance calculations can misoperate if not set properly.

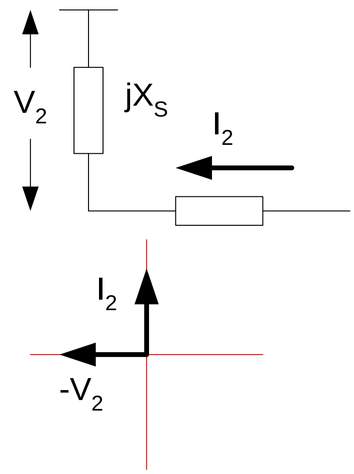

Fig. 19. Negative-sequence voltage polarized directional decision for reverse fault (CCW rotation)

If the distribution system is radial following the first trip, then directional elements can be disabled if necessary to prevent misoperations and rely upon traditional coordination.

VII. CONCLUSIONS

The paper demonstrates how to perform high speed communication-assisted tripping and sectionalizing on distribution systems. All faults are quickly cleared and the distribution system is rapidly sectionalized to restore service to the most customers possible. Inherent time delays embedded in the traditional approach are eliminated.

ABOUT THE AUTHOR

Steve Turner is a Senior Applications Engineer at Beckwith Electric Company. His previous experience includes working as an application engineer with GEC Alstom, an application engineer in the international market for SEL, focusing on transmission line protection applications. Steve worked for Progress Energy, where he developed a patent for double-ended fault location on transmission lines.

Steve has both a BSEE and MSEE from Virginia Tech University. He has presented at numerous conferences including: Georgia Tech Protective Relay Conference, Western Protective Relay Conference, ECNE and Doble User Groups, as well as various international conferences. Steve is a senior member of IEEE.