

Switch Onto Fault: Maintaining Dependability, Security, and Speed

Rohith Poduval
NIPSCO

Ryan McDaniel and Sujay Dasgupta
Schweitzer Engineering Laboratories, Inc.

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Rohith Poduval, *NIPSCO*

Ryan McDaniel and Sujay Dasgupta, *Schweitzer Engineering Laboratories, Inc.*

Abstract—Switch onto fault (SOTF) schemes trip a transmission line breaker when the breaker closes into a faulted line. The scheme is typically enabled when a breaker is opened and disabled if healthy line side voltage is detected. This paper discusses SOTF settings for dependable fault coverage and security for heavy load conditions when SOTF voltage reset is not available. A case study is included to illustrate the speed sacrifices made when a distance element, rather than an instantaneous element, must trip during an SOTF condition.

This paper also discusses the effects of source impedance ratio and considerations during use of high-speed reclosing.

I. INTRODUCTION

Switch onto fault (SOTF) trip logic provides a window of time for the enabling of nondirectional relay elements and instantaneous overreaching directional elements after the circuit breaker closes to energize a line. If the circuit breaker closes into an existing fault condition, the fault must clear as fast as possible to minimize equipment damage. A common case to consider during SOTF is closing a breaker into a set of three phase grounds that field personnel failed to remove prior to re-energizing the line. However, any fault type can exist during an SOTF condition, and the fault can be anywhere along the protected line. Because of this, overreaching phase and ground distance zones must also be enabled during SOTF conditions.

To better understand the SOTF scheme, consider a line protection relay such as shown in Fig. 1 in which line-side potential transformers are denoted by flags. The SIR (L, F) is the ratio of the source impedance, ZS (L, F), to the line impedance, ZL. Reference [1] discusses calculation of SIR in detail. Let us consider a case of line energization in which the breaker that closes in first is called the leader (denoted by L) and the breaker that closes in second is called the follower (denoted by F).

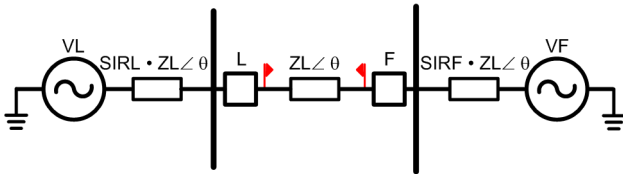


Fig. 1. Example homogeneous system

No voltage is available to the relay prior to the leader breaker closing. If the leader breaker closes into a close-in three-phase fault, directional relay elements have no usable polarizing voltage and does not enable. To achieve dependability for close-in three-phase faults during SOTF conditions, we briefly

enable a nondirectional element. The leader breaker is not tying the line to a bulk energy system, so there is no need to set a nondirectional element in consideration of load. This element can be set just greater than line charging current or tapped load conditions to maintain security. A directional overreaching distance element has no security concerns; the follower is open, so no overreach can occur. With instantaneous overreaching directional zones enabled during SOTF, you can clear end-of-line faults without time delay.

On the follower side, line potential is available prior to breaker closing, so directional elements may be available if the relay allows use of line potential to polarize directional elements with a breaker open. In this case, you can use switch onto fault reset (SOTFR) to disable nondirectional and overreaching directional elements. However, SOTFR can be unsuccessful if there is voltage unbalance on the system. In cases of SOTFR failure, the nondirectional and overreaching directional elements are in service when the follower breaker closes.

When the follower breaker is closed, any enabled elements must be set above the North American Electric Reliability Corporation (NERC) loadability limit because the line becomes a part of the bulk energy system [2]. If you use voltage supervision in conjunction with a nondirectional element, you can extend the reach of the nondirectional element. This means that you can set instantaneous phase elements (50P) lower than the line loadability limit. If the set point of the voltage supervision (27P) is below 0.7 pu, the 50P, according to [2], has no lower threshold guidance on pickup settings. Aside from setting the 27P greater than induced voltages from adjacent lines, there is no guidance on a lower-boundary condition for 27P pickup settings. However, if you set 27P too low, you risk defeating 50P protection. Throughout this paper, 27P undervoltage supervision means that all three phases must be below the 27P set point.

Reference [2] describes possible delayed operation for three-phase faults during SOTF conditions, but relay manufacturers provide little information regarding distance element performance should you close into faults that produce a low amount of polarizing voltage. Such information is important for determining the lower boundary condition for setting the 50P undervoltage supervision.

SOTF protection adds dependability for close-in three-phase faults, but it also improves tripping speed for all fault types down the line. The latter, one of the key motivations behind this paper, is illustrated in Section II.

II. EVENT DISCUSSION

On May 23, 2019, a storm caused Northern Indiana Public Service Company to experience several outages on 138 kV and 69 kV circuits across its service territory. This storm caused broken poles on the 138 kV circuit near the substation. Fig. 2 shows a one-line diagram of the substation (in which the 138 kV circuit on Line 1 is protected by Relay A and Relay B).

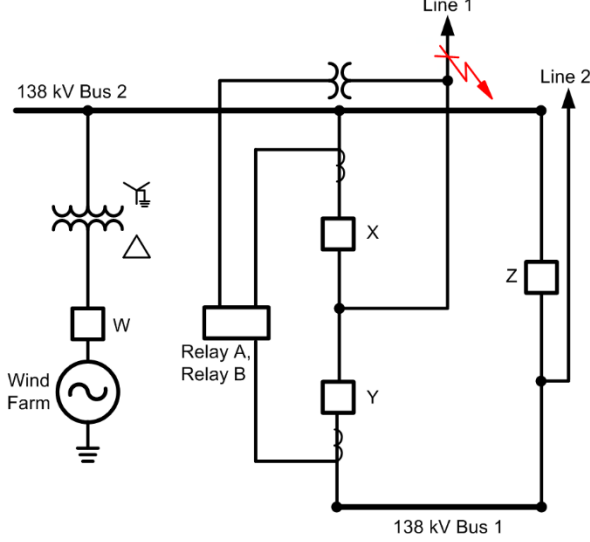


Fig. 2. Substation one-line diagram

The event reports retrieved from the relays indicate that a Line 1 fault started as a B-G fault and eventually evolved into a three-phase fault, once again confirming that faults do not improve over time. The subsequent section details the sequence of operation for the relays during the storm.

A. Sequence of Events

At 1:11:25.40 a.m., Relay A tripped on the Zone 1 distance element in response to the B-G fault on Line 1 at 1.8 miles from the substation, as can be seen in Fig. 3. This trip caused Breaker X and Breaker Y to open.

Five seconds after the initial fault cleared, the breaker control relay reclosed Breaker Y. The B-G fault was now a three-phase fault at 1:11:30.64 a.m., and Relay B tripped on the Zone 1 distance element (M1P), as shown in Fig. 4. There were no events triggered in Relay A; Relay B used a different memory polarization method than Relay A to make a trip decision.

Fifteen seconds after the previous fault, the breaker control relay reclosed Breaker Y. Relay A encountered another three-phase fault and tripped on Zone 1 and Zone 2 distance elements, but at a delay of 9.25 cycles (154 ms), as shown in Fig. 5. The 9-cycle delay in tripping was slow for a Zone 1 element and warrants further investigation.

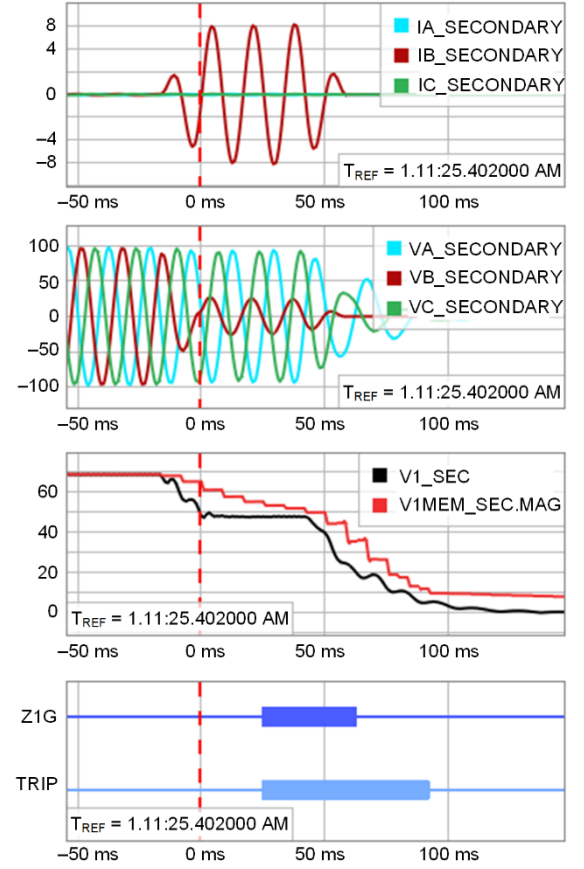


Fig. 3. Relay A B-G fault on Line 1

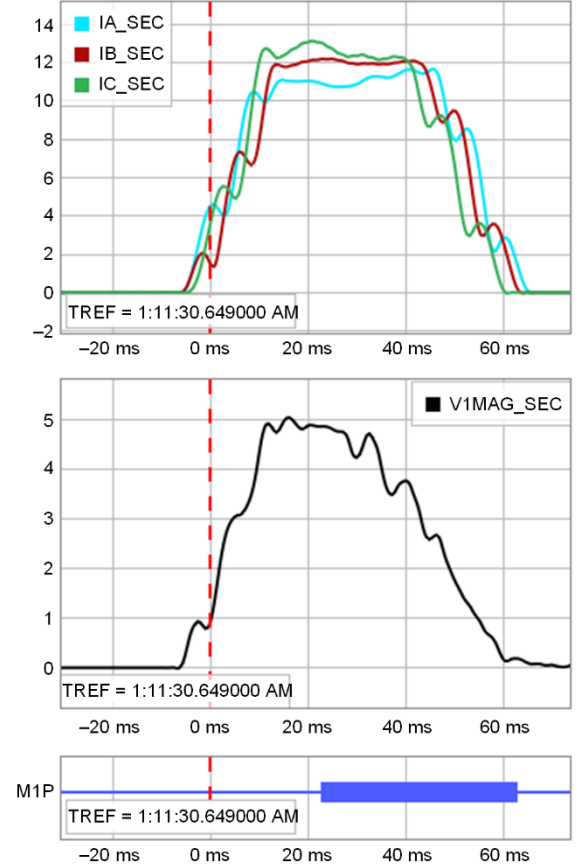


Fig. 4. Relay B three-phase fault

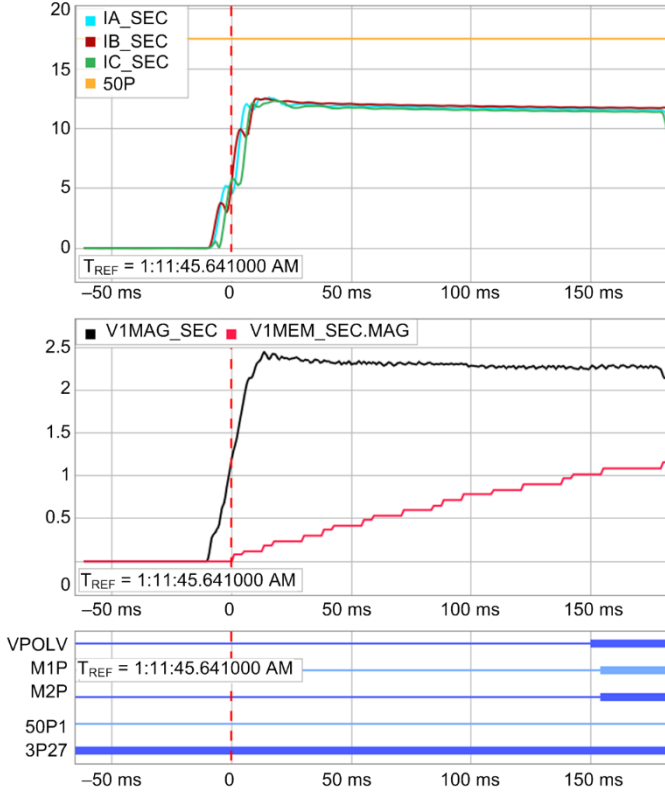


Fig. 5. Relay A three-phase fault

B. Root Cause of Relay A Delayed Operation

The Relay A SOTF settings in service at the time of trip are shown in (1).

$$\text{SOTFT} = \text{M2P} + \text{Z2G} + 50\text{P} \cdot 3\text{P27} \quad (1)$$

The 50P was set at 17.50 A secondary, but the fault current was about 12 A secondary, as can be seen in Fig. 5. The 50P element was effectively disabled because of a high set point, so the relay relied on directional distance elements to clear this fault. The wind farm was out of service at the time of this event, lowering the overall contribution to the three-phase fault. It is important to set the 50P element to be reliable under a worst-case single contingency. In this case, the 50P element should have been set with adequate pickup with the wind farm out of service. Ultimately, the root cause of the slow trip time in this event was the 50P element being set too high.

C. Positive-Sequence Memory Voltage ($V_{1\text{MEM}}$)

Relay A uses positive-sequence memory voltage ($V_{1\text{MEM}}$) to polarize the distance elements. As shown in Fig. 5, the VPOLV word bit (sufficient positive-sequence polarizing voltage present) asserts just prior to the trip of the relay. VPOLV asserts when the $V_{1\text{MEM}}$ exceeds 1 volt. MHO elements are disabled until VPOLV is asserted. Closing into a three-phase fault causes delayed tripping (9 cycles delay) because $V_{1\text{MEM}}$ ($V_{1\text{MEM_SEC.MAG}}$) takes 9 cycles to charge to a value of 1 V. Relays can employ various methods to achieve a reliable memory signal. Relay A and Relay B, for example, use different $V_{1\text{MEM}}$ polarization techniques, leading to different performance of each relay when energizing into this fault. Relay designers can elect to vary time constants for various

system conditions. A time constant is the time necessary for a fully charged $V_{1\text{MEM}}$ to decay about 36.7 percent. The memory polarization/memory charging method described at the end of this section applies only to Relay A and should not be considered the method by which all relays implement this feature.

If the positive-sequence fault voltage (V_1) exceeds 5 V, a short time constant is employed because memory is not critical. Enough fault voltage exists to reliably and securely operate. A short time constant means the magnitude of $V_{1\text{MEM}}$ closely follows the magnitude of V_1 . A short time constant is advantageous because the relay can maintain better security during large frequency excursions [3].

If V_1 is less than 5 V, a long time constant is used. This means that $V_{1\text{MEM}}$ magnitude decays slowly under a sudden and severe reduction of V_1 . Using a long time constant maintains directionality under close-in three-phase fault conditions for an extended period. This is important for close-in reverse three-phase faults for which it is necessary to maintain a block signal to the remote terminal in a directional comparison blocking (DCB) scheme. It can also be important for forward three-phase faults in high SIR conditions so that a time-delayed Zone 2 element can time out. The disadvantage of longer time constants is that they can reduce relay security for frequency excursions [3].

You can implement charging memory voltage in various ways. In Relay A, the relay charges at the long time constant until V_1 exceeds 5 V and then switches to the short time constant. We can see in this particular relay, if the fault voltage during an SOTF condition is less than 5 V, speed penalties result.

Fig. 6 shows us the actual time it takes $V_{1\text{MEM}}$ to reach 1 V for this fault (orange line), and, hypothetically, how long it would take to reach 1 V if the short time constant charging had been used. There is a difference of 110 ms. Clearly, how a relay designer handles charging polarization voltage significantly affects trip times when energizing a line into a three-phase fault.

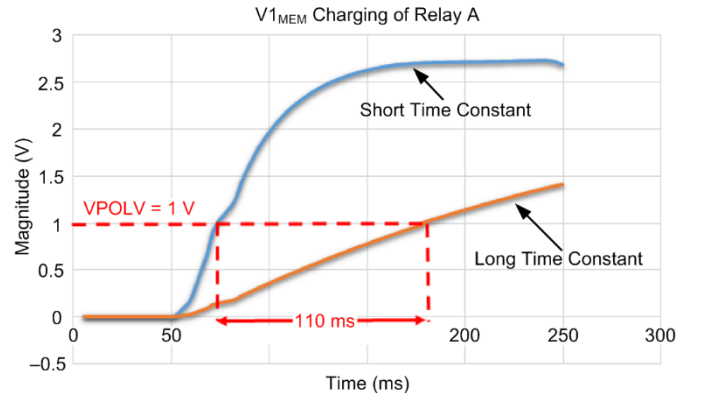


Fig. 6. Positive-sequence memory voltage during charging

III. TESTING

For a better idea of how different relays respond to closing into three-phase faults, we performed three-phase fault line energization tests on four different relays and compared the trip

operate time. In these tests, the Zone 2 phase element was evaluated and set to 150 percent of the protected line.

A. Distance Element Trip Time for Various Source Impedance Ratios

Fig. 7, Fig. 8, and Fig. 9 show the results from the test to analyze different relay operate speeds for $SIR = 1, 3$, and 5 . For $SIR = 1$, we see that relay operation was delayed or disabled for faults at less than 9 percent of the line. In addition, we would describe any tripping time longer than 250 ms as not only slow but undependable because a remote backup zone would likely trip for the fault. For faults beyond 15 percent, the relays tended to operate in a band of 41–15 ms.

For $SIR = 3$, there was delayed relay operation or no operation for faults at less than 20 percent of the line length. For faults beyond 40 percent, the relays tended to operate in a band of 44.5–15 ms. For $SIR = 5$, relay operation was delayed or disabled for faults at less than 50 percent of the line, whereas for faults beyond 60 percent of the line, relays operated in a band of 45–15 ms.

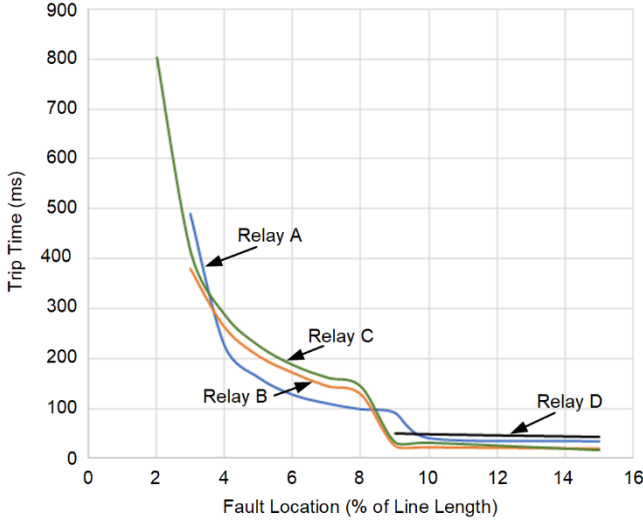


Fig. 7. Relay operation times for various fault locations when $SIR = 1$

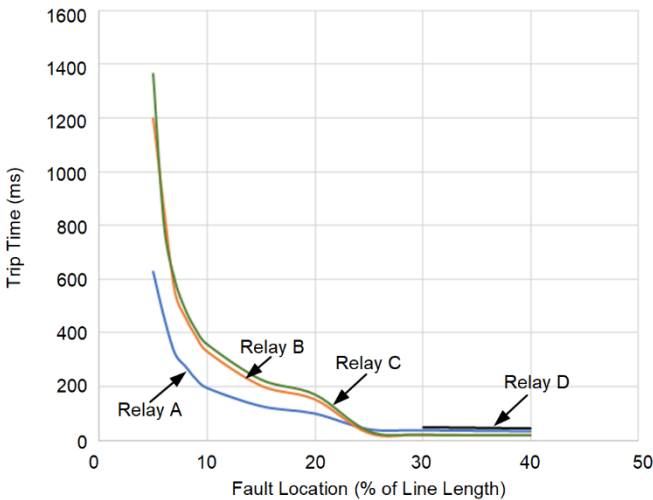


Fig. 8. Relay operation times for various fault locations when $SIR = 3$

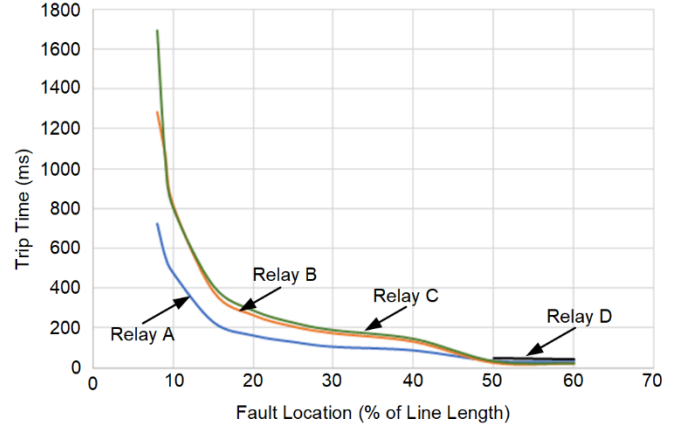


Fig. 9. Relay operation times for various fault locations when $SIR = 5$

B. SOTF Speed

In an SOTF scheme, the instantaneous phase overcurrent element (50P) is included to provide quick operation. However, 50P is usually supervised with an undervoltage element (27P) to increase security in cases such as line energization and tapped load inrush. Fig. 10 shows common logic implemented to protect against phase faults during SOTF. The output is SOTFT (switch onto fault trip).

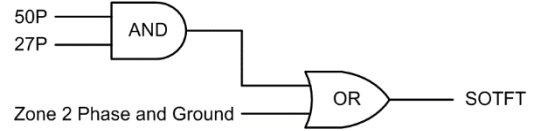


Fig. 10. SOTF trip logic

We tested with a 50P set with 1.5 times pickup for an end-of-line fault and various undervoltage (27P) pickup settings for $SIRs$ 1, 3, and 5 for a three-phase SOTF condition. We observed that a higher setting of 27P extends the reach of SOTF and is faster for three-phase faults down the line. We compared these results with a nondirectional mho characteristic (offset mho) available in Relay D. Both forward and reverse reach were set at 150 percent of the protected line impedance. We discuss this element in Section IV.

As shown in Fig. 11, a 30 V setting of 27P provides faster operation time, compared to settings of 5 V and 15 V, for faults beyond about 40 percent of the line with $SIR = 1$. For faults beyond about 20 percent for $27PPU = 5$ V and about 40 percent for $27PPU = 15$ V, the SOTFT operation time begins to fall back to M2P operation time (about 32 ms). For $SIR = 3$ and higher, a 27P setting of 30 V and 15 V yields similar speed performance, operating no slower than 18 ms. A 27P setting of 5 V effectively disables the phase overcurrent element at higher SIR values. Note in Fig. 11 that the nondirectional offset mho characteristic of Relay D is faster for nearly all fault cases. It has an approximate fixed operating time of 12 ms for all fault locations and all $SIRs$ tested.

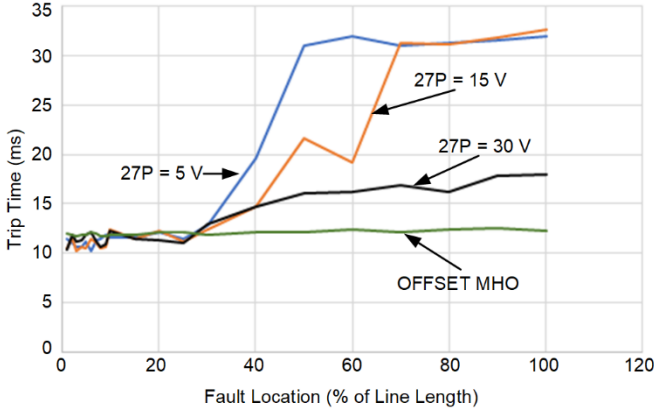


Fig. 11. Relay operation time for various fault locations for different 27P pickup and offset mho characteristic for SIR = 1

C. Phase-to-Phase and Phase-to-Ground Faults

We tested the speed of operation for directional Zone 2 distance elements for phase-to-phase and phase-to-ground faults for SIR = 1, 3, 5, and 10. For phase-to-phase faults, the relays operated in a band of 36.2–17.1 ms. For phase-to-ground faults, the relays operated in a band of 47.9–26 ms.

For a close-in phase-to-phase fault, the minimum available positive-sequence voltage is 0.5 pu. For a close-in phase-to-ground fault, the minimum positive-sequence voltage is 0.67 pu. Both cases are well above any conditions that would block the 21 elements from operating. However, directional distance elements operate slower for SOTF unbalanced fault conditions than for conditions in which the line is already energized.

IV. NONDIRECTIONAL DISTANCE ELEMENT

The nondirectional distance element offers many benefits in regard to SOTF protection, particularly in cases in which a leader breaker closes into a line to energize tapped loads or when line charging current is exceptionally high. The use of a nondirectional distance element allows the relay user to more precisely define the operating zone of SOTF over 50P or 50P AND 27P implementations. This leads to greater security in line energization cases for which large non-fault currents are present. In addition, because the zone is nondirectional, it is inherently dependable for close-in faults in which no fault voltage is available at the relay location. The general formula for a nondirectional mho is given in (2), where I and V are the fault loop current and voltage. The element operates when $T > 0$.

$$\begin{aligned} S1 &= IZ_{\text{FORWARD}} - V \\ S2 &= IZ_{\text{REVERSE}} + V \\ T &= \text{RE}(S1 \cdot S2^*) \end{aligned} \quad (2)$$

As with directional elements, six fault loops are calculated (AB, BC, CA, AG, BG, and CG) and individual settings are available for the phase and ground loops. The non-directional mho has two reach settings: a forward reach (Z_{FORWARD}) and a reverse (Z_{REVERSE}) reach. The forward reach is equivalent to

reach settings used in directional distance elements and follows along a settable maximum torque angle (MTA). The reverse reach allows the relay user to extend the reach behind the relay to a fixed point so that the relay location is included in the operating characteristic. The element uses only fault loop currents and voltages (no memory voltage is used), so the characteristic is static. This means that the element operates for reverse faults within the Z_{REVERSE} setting. Because of this, this element only trips with no intentional time delay in SOTF applications. This characteristic is sometimes referred to as an offset mho because the circle is permanently offset from the origin. We can see in (2) that if $V = 0$ (close-in fault), the $S1$ and $S2$ signals are in phase and that this leads to a positive torque condition that results in an operate.

Fig. 12 illustrates the characteristic for the formulas in (2). When a leader breaker closes to energize an unfaulted line and current is present, the apparent impedance either appears in Quadrant 1 or Quadrant 4. For lines with tapped loads, the apparent impedance tends to be in Quadrant 1 near the +R axis. For lines with large charging currents, the apparent impedance tends to be in Quadrant 4 near the $-X$ axis. You can either set the Z_{REVERSE} setting short to allow more security in tapped load or high charging current scenarios or set it long to increase sensitivity for fault detection during unloaded lines with low charging current. You should set the Z_{FORWARD} setting similarly to directional overreach zone reaches.

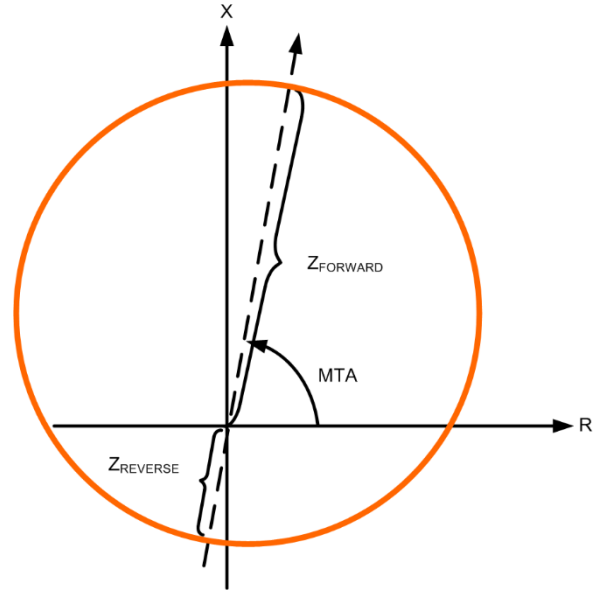


Fig. 12. Nondirectional mho distance element

For even more flexibility, you can use a nondirectional quadrilateral element to exactly refine the reach along the R and X axes, as shown in Fig. 13.

Although the nondirectional quadrilateral element offers more flexibility for load/line charging current scenarios, two additional settings are required: R (the reach along the R axis) and TILT (allows the user to adjust the reactance line for security).

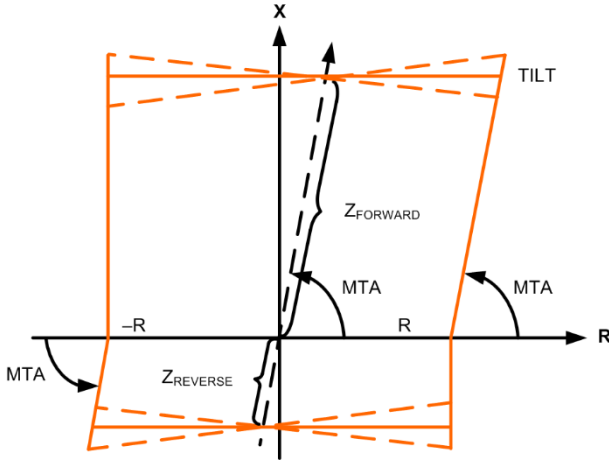


Fig. 13. Nondirectional quadrilateral element

V. SOTF SETTING CONSIDERATIONS

Overly conservative security and slow tripping speed result if the sole consideration in setting SOTF is achieving dependability for close-in three-phase faults when the leader breaker closes. In this section, we discuss considerations for SOTF protection during the use of three types of tripping elements: overcurrent only (50P), overcurrent with voltage supervision (50P AND 27P), and nondirectional distance (offset mho). To compare a nondirectional distance element reach directly to an overcurrent pickup, we describe how to plot the overcurrent pickup and voltage pickup in the impedance plane.

A. Plotting 50P in the Impedance Plane

An overcurrent must be set high enough to maintain security for tapped loads and line charging current. It must be set low enough to issue a trip for a close-in three-phase fault in a worst-case single contingency condition [2]. This means we must be able to detect a close-in fault with remote end open and the strongest source behind the relay location out of service. Going forward, we refer to this condition as SIR_{WEAK} . We can gain speed for three-phase faults along the line by reducing the 50P element setting.

A $50P_{PU}$ setting of 1.5 times pickup for an end-of-line three-phase fault with SIR_{WEAK} provides dependability, with margin, for all bolted three-phase faults along the line. A 1.5 times pickup (M_{50P}) also offers tripping times faster than 1.5 cycles (25 ms) in most relays for all bolted three-phase faults. Although $M_{50P} = 1.5$ may seem a low pickup value, recall that if fault resistance is present in a three-phase fault, it reduces the overall fault current and raises the fault voltage the relay detects, making it more likely that a directional mho operates. A setting of $M_{50P} = 1.5$ still offers more than adequate three-phase fault resistance coverage.

To visualize the reach of a 50P element in the impedance plane, we reference Fig. 1. The leader breaker is closed and the follower breaker is opened. Equation (3) defines the current seen for a three-phase bolted fault at the end of the line on a homogenous system, where ZL is 1 pu.

$$\frac{1}{(SIRL \cdot (1\angle\theta) + ZL)} = I_{RELAY} \quad (3)$$

If we want to set a 50P element to detect all three-phase line faults, we set our 50P element below the resultant I_{RELAY} . We would do this under the highest expected single contingency SIR condition.

In (4), we define the relay pickup setting ($50P_{PU}$) in terms of M_{50P} (multiples of pickup) and weak source conditions ($SIRL_{WEAK}$).

$$\frac{1}{M_{50P} \cdot (SIRL_{WEAK} + 1)} = 50P_{PU} \quad (4)$$

If we then take (3) divided by (4), we obtain the ratio relay fault current (I_{RELAY}) to relay set point ($50P_{PU}$). We are interested in the case in which $|I_{RELAY}| = 50P_{PU}$. We note that I_{RELAY} can be at any angle. Equation (5) shows (3) divided by (4) and set equal to $1\angle\phi$.

$$\frac{M_{50P} \cdot (SIRL_{WEAK} + 1)}{SIRL \cdot (1\angle\theta) + ZL} = 1\angle\phi \quad (5)$$

Solving for ZL yields (6).

$$\frac{M_{50P} \cdot (SIRL_{WEAK} + 1)}{1\angle\phi} - SIRL \cdot (1\angle\theta) = ZL \quad (6)$$

Equation (6) defines ZL , a complex number that represents the per-unit line impedance reach of a 50P element. This is a circle with a center at $-SIRL\angle\theta$ and a radius equal to $M_{50P} \cdot (SIR_{WEAK} + 1)$. The radius of the 50P element is a function of M_{50P} , so a relay user can control this. However, the source impedance defines the center of the circle. Therefore, the overall reach of the 50P element for three-phase faults varies with SIR .

Consider $M_{50P} = 1.5$ and $SIRL_{WEAK} = 5$, and $\phi = \theta$ (bolted fault) and we want to find ZL for this system condition. We arrive at $ZL = 4$. This means that for a 50P set at 1.5 times multiple pickup for an end-of-line three-phase bolted fault, the 50P reaches to four times the actual line length in the impedance plane. If the SIR changes to 1, but the $50P_{PU}$ setting is still set based on $SIRL_{WEAK}$, ZL evaluates to 8. This means that when you set a 50P based on a single contingency, the reach of 50P can be quite long under normal system conditions.

B. Plotting 27P in the Impedance Plane

A 50P element can have exceptionally long reaches when you attempt to maintain dependability for three-phase faults for the entire length of the line. Therefore, it is common to supervise 50P with 27P to effectively reduce the reach of the 50P element. The leader breaker can use this additional security when you close into tapped loads or large line charging currents. The follower can also use this additional security if SOTF fails to reset after the leader breaker closes.

Equation (7) defines the relay voltage for the system in Fig. 1.

$$1 - \frac{SIRL\angle\theta}{(SIRL\angle\theta + ZL)} = V_{RELAY} \quad (7)$$

Solving for ZL, we obtain (8), which defines the fault location in per-unit ZL based on the measured relay voltage and the system SIR.

$$\text{SIR}L\angle\theta\left(\frac{1}{1-V_{\text{RELAY}}}-1\right)=ZL \quad (8)$$

V_{RELAY} can be at any angle, so (8) represents a circle. We can find the center of that circle by solving for ZL with $V_{\text{RELAY}}\angle 0^\circ$ and $V_{\text{RELAY}}\angle 180^\circ$. The midpoint of these two evaluations represents the center of the circle for a given magnitude of V_{RELAY} and is shown in (9).

$$\text{SIR}L\angle\theta\left(\frac{1}{1-|V_{\text{RELAY}}|}-1\right)=ZL_{\text{CENTER}} \quad (9)$$

We can obtain the radius shown in (10) by subtracting (9) from (8).

$$\text{SIR}L\left(\frac{|V_{\text{RELAY}}|}{1-|V_{\text{RELAY}}|^2}\right)=ZL_{\text{RADIUS}} \quad (10)$$

We can substitute $27P_{\text{PU}}$ (27P pickup setting) for $|V_{\text{RELAY}}|$ to find the circle that defines the reach of 27P.

Fig. 14 shows the reach of $27P_{\text{PU}}$ settings (up to 0.5 for SIRs of 1, 3, and 5 for bolted three-phase faults) that we obtain from (8).

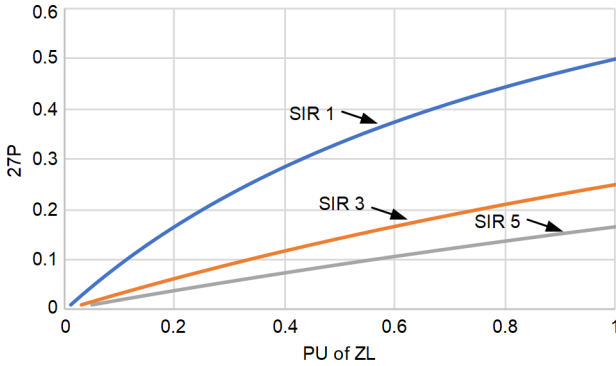


Fig. 14. 27P reach for 3P faults on a radially fed transmission line

For low SIRs, the effective reach of a low-set 27P for 3P faults can be quite short. One can assume that the reach of the 50P supervised by a 27P would be equal to the common area of 50P (6) and 27P (9) and (10). However, testing reveals that a 50P supervised by a 27P when closing into three-phase faults reaches farther than expected. For example, a 15 V $27P_{\text{PU}}$ setting (66.4 V nominal) for an SIR of 1 provides a 27P reach of about 29 percent of the line (much shorter than the 50P reach). However, the 27P AND 50P reach for closing into a three-phase fault is between 60 to 70 percent. From Fig. 11, we can see that the SOTF speed with $27P_{\text{PU}} = 15$ V is fast for faults to as far as 60 percent of the line. Beyond this fault location, the 27P and 50P do not operate reliably and SOTFT speed falls back to the operation time of M2P.

C. Plotting 50P Supervised With 27P in the Impedance Plane

To explain why a 50P supervised by 27P reaches farther than expected when closing into three-phase faults, first consider a three-phase fault that occurs well after the leader breaker has been closed. In this case, neither the 50P nor 27P is asserted prior to the fault because healthy voltage is present and no fault current is present. When the fault occurs, the 50P must assert and the 27P must assert. Regardless of the time it takes either element to assert, each element must be asserted for the final trip output. In this scenario, the reach is strictly defined by the common area shared by the 50P and 27P element in the impedance plane.

When you switch into a three-phase fault, the 27P is initially asserted and the 50P is initially deasserted. There is a race condition, and the resultant reach is a function of how long each element takes to change state. If the 27P drops out before 50P asserts, we have a no-operate condition. If the 50P asserts before the 27P drops out, we have an operate condition. When the 50P and 27P change state at the same time, this is the balance point or the reach of voltage-supervised 50P. If we assume the filtering delay is the same for voltages and currents, the speed of each element, and therefore the reach, is directly related to multiples of pickup for each element. Equation (11) shows how we can relate the speed of the 27P and 50P elements to determine the overall reach. We add the variable M_{27P} , which is multiples of pickup for the 27P element.

$$\frac{|V_{\text{RELAY}}|}{27P_{\text{PU}}} = M_{27P} = \frac{|I_{\text{RELAY}}|}{50P_{\text{PU}}} = M_{50P} \quad (11)$$

Using previously defined equations and solving for $|ZL|$, we can define the reach of a 50P element supervised by 27P during line energization in (12).

$$(\text{SIR}_{\text{WEAK}} + 1) \cdot M_{50P} \cdot 27P_{\text{PU}} = |ZL| \quad (12)$$

Equation (12) defines a circle centered at the origin with a radius equal to $|ZL|$. We can see that as M_{50P} increases (lower $50P_{\text{PU}}$ setting) and $27P_{\text{PU}}$ increases, the reach extends. We note that the ZL from (12) cannot exceed the ZL from (6) (the voltage-supervised 50P cannot reach farther than just the 50P alone). We refer to (12) as the reach of (27P AND 50P) (SOTF) going forward.

To test this equation, a test set was used to shoot the impedance characteristic for a 50P supervised with 27P for three-phase faults under a constant SIR condition. Equations (9) and (10) were used to draw a circle in the impedance plane if there are healthy voltages prior to the faults (the 27P characteristic for this test was smaller than 50P). Equation (12) was used to draw a circle in the impedance plane if there is no voltage prior to the fault. For this test, the SIR was 1 and $27P_{\text{PU}} = 0.452$ (30 V, 66.4 V nominal PG voltage). M_{50P} was set at 1.5 for an SIR = 1. A fully inductive system was simulated.

The maximum expected reach for a three-phase bolted fault is about 82 percent of the line when healthy three-phase voltage is available prior to the fault, and testing validates this. In the inner circle in Fig. 15, we can see that all performed tests plot within a 5 percent error of the expected circle (green.)

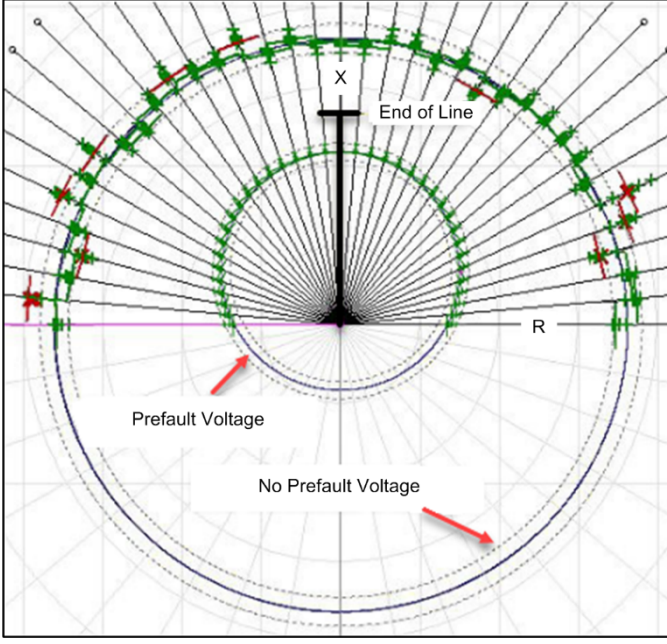


Fig. 15. 50P supervised with 27 P for three-phase faults with healthy voltage and without healthy voltage prior to fault

The maximum expected reach for a three-phase bolted fault is about 136 percent of the line when no voltage is available prior to the fault. In the outer circle of Fig. 15, we can see that most of the tests fall within the expected reach (green). Some of the tests fall outside of the 5 percent tolerance, but even the tests that do fall out of the 5 percent tolerance are still generally close to the expected circle.

Equation (12) provides a general idea of the reach of a 27P-supervised 50P when you energize the line. Although not exact, (12) shows us that (27P AND 50P) (SOTF) reaches a bit farther than expected in the impedance plane for a short duration after line energization. However, once the line is energized, the tripping characteristic shrinks to the common area of 27P and 50P in the impedance plane.

D. Characteristic Comparison

Based on the previous discussion, it is possible to plot the response of the 27P, 50P, (27P AND 50P) (SOTF), and nondirectional mho in the impedance plane. Fig. 16 shows the results for $SIR_{WEAK} = 5$, $M_{50P} = 1.5$, and $27P = 0.5$ pu. The nondirectional mho forward and reverse reach is set at 1.5 pu of ZL.

From Fig. 16, we see that the (27P AND 50P) (SOTF) reach area for line energization is quite large compared to the nondirectional overreaching mho, but it is significantly less than the reach area of 50P alone. We note that (27P AND 50P) (SOTF) cannot extend past the reach of the 50P alone, so the

top of the characteristic tends to flatten a bit in this example. Even if the line is already energized, the reach of the 27P AND 50P is also quite long (common area of 27P and 50P). Clearly the nondirectional mho has better security because the tripping area is smaller. We simply have better control over the reach with an impedance characteristic. We can more easily limit exposure to line charging current and tapped loads on the line.

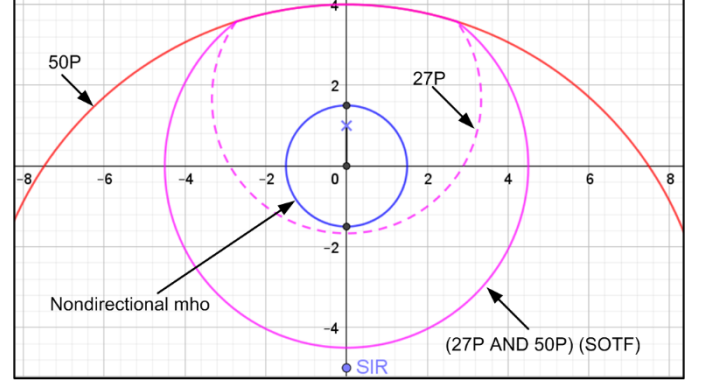


Fig. 16. Characteristic comparison for $SIR = 5$

It is possible to limit the reach of (27P AND 50P) (SOTF) by rearranging (12) and finding a 27P that satisfies a given reach ZL. For example, if you want the ZL per-unit reach to be 1.5 and you set the $50P_{PU}$ such that $M_{50P} = 1.5$ for an end-of-line fault with SIR_{WEAK} , you can use (13) to set $27P_{PU}$.

$$27P_{PU} = \frac{1}{(SIR_{WEAK} + 1)} \quad (13)$$

In this example ($SIR_{WEAK} = 5$), setting 27P at 0.167 pu limits the reach of (27P AND 50P) (SOTF) to 1.5 per unit of ZL. The reach is approximate, and it theoretically does not change for varying system conditions during line energization. This is a good balance between dependability, speed, and security. In addition, if you take the results from (13) and plug them into (8), the voltage setting reaches exactly to the end of line for cases in which the line is already energized under single contingency conditions. In summary, when using (13) with a $M_{50PU} = 1.5$, you get a short duration transient that allows adequate line coverage when you close into a bolted three-phase fault on the line.

There are boundary conditions for $27P_{PU}$. Set it lower than 0.7 to accommodate NERC criteria. Set it high enough to operate when directional elements are still slow. Our testing shows that the distance element operating speed was less than 3 cycles for three-phase SOTF conditions when the available fault voltage at the relay was 0.1 pu or greater, so you should not set $27P_{PU}$ lower than 0.1. Therefore, for SIR_{WEAK} between 0.43 and 9, you can follow (13) if you so desire.

Clearly, it is much easier to set a nondirectional distance element than to use any of the other available characteristics to provide fast, secure, and dependable protection. With a nondirectional distance element, concerns over SIR, end-of-line fault current, multiples of pickup, and 27P/50P racing conditions all vanish.

VI. ADDITIONAL CONSIDERATIONS

In this section, we discuss additional considerations when applying SOTF.

A. SOTF Duration Timer Window

Many relays allow the user to set the SOTF duration window that defines how long SOTF elements are enabled after the breaker is closed. For security, set the window as short as possible. For dependability, set the window as long as the breaker failure time in the relay, with margin. Consider a close-in three-phase fault that occurs on breaker close, but the breaker fails to open. If the SOTF window is shorter than the time it takes the breaker failure to time out, a local breaker failure does not clear the fault, resulting in more outages than necessary.

B. Enabling SOTF

Typically, you can enable SOTF in two ways: (1) at the moment a breaker opens (usually with low current detection and 52A contact deassertion) or (2) upon the detection of a close issued in the dc control circuit. Method 2 ensures that SOTF is only enabled at the moment breaker(s) protecting the line are closed, but it requires a relay input in the close circuit to determine that a breaker close has been issued. The following illustrates a case in which Method 1 can have a security issue if a 52A contact fails on a lightly loaded or unloaded line.

In Fig. 17, Breakers 3004 and 3005 are closed and Breaker 3006 is open. Relay A operates for an out-of-zone phase-to-ground fault that was sourced by the wye/delta transformer (zero-sequence only). As shown in Fig. 18, breaker contact status (52A) was deasserted throughout the event, indicating that the breaker auxiliary contact was not functioning. With no current present prior to the fault and 52A = 0, SOTF enabled. When the ground fault occurred, the relay tripped because of the assertion of 50G (ground overcurrent).

Typically, a sensitively set 50G element is not part of SOTF logic. It can be a security concern upon energizing a loaded line when the breaker poles close unevenly. Also, tapped loads with transformer inrush can lead to uneven CT saturation because of uneven dc offset in the three poles and produce false ground current. There can be some gains in speed and sensitivity for high-resistance faults, but one must weigh the benefits versus the risks of using 50G.

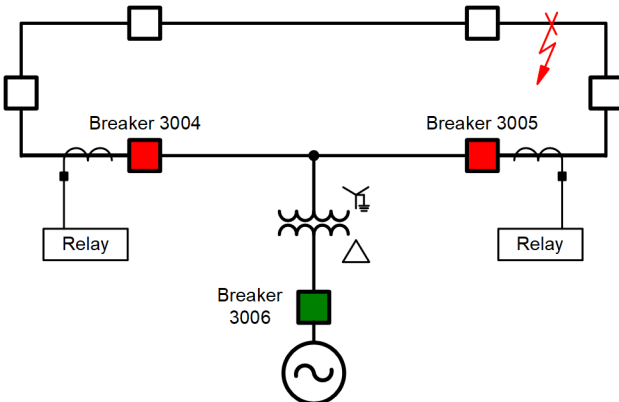


Fig. 17. System diagram

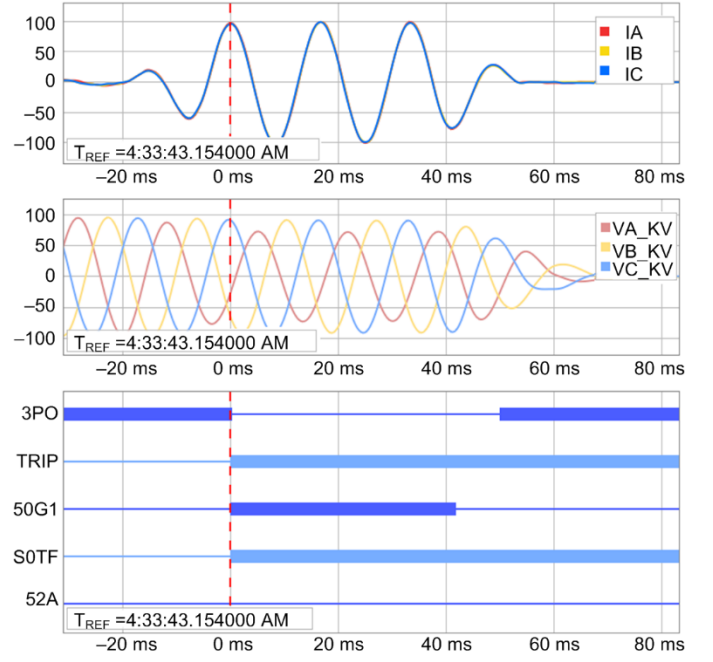


Fig. 18. SOTF trip event

Method 2 would not allow you to enable SOTF after the breaker closes (plus SOTF window time) even if the 52A contacts malfunction.

C. Resetting SOTF With Healthy Line Voltage

Resetting SOTF in the follower or leader with healthy line voltage allows you to disable nondirectional tripping elements because healthy voltage is available to polarize the directional elements. This allows you to set SOTF elements without respect to load because they are not enabled when you tie the line together. However, there can be speed and dependability concerns in some unlikely scenarios.

1) POTT Delayed Line Clearing

Consider a case in which the leader breaker closes and then resets SOTF on healthy line voltage. Before the follower breaker closes, assume a fault occurs near the follower terminal. In this case, the leader relay detects the fault in a permissive overreaching zone of protection and keys permission to the follower. The follower breaker is open, so the follower relay does not detect this fault. In a traditional POTT scheme, the leader must trip upon assertion of the time delay overreaching element for this fault. However, if a hybrid POTT scheme allowing the follower to echo the key back to the leader during open breaker conditions is in service, the leader can trip fast for this scenario.

A DCB scheme allows fast clearing of the line via the leader (the follower does not send a block signal).

2) Out-of-Synchronization Closing

When the leader breaker closes, the follower relay asserts SOTFR and uses the voltage supplied by source VL in Fig. 1. to polarize the directional elements in the follower relay. Generally, this is of no concern, but consider a case in which there is a large angle and/or frequency difference between VL and VF and the follower breaker is closed accidentally out of

synchronization. Consider also that a close-in three-phase fault occurs at the follower terminal upon the closing of the breaker. Because the follower relay is essentially being polarized by something close to VL, but the fault is fed by VF, the directional elements for the relay may fail to operate. The follower may also declare the fault in the reverse direction and prevent any communications-assisted tripping by the leader breaker.

Although these scenarios are unlikely, refusing to use SOTFR allows nondirectional elements to remain in service when closing the follower or leader breaker so that these scenarios can be cleared quickly. Any in-service elements when the follower closes must meet NERC loadability criteria. If you are using a 50P element, use 27P supervision.

D. Bus Potential Transformers (PTs)

The primary reason to use SOTF with bus PTs is to allow high-speed clearing for an end-of-line fault via the overreaching directional/nondirectional elements when the leader breaker closes. To maintain high-speed clearing for SOTF conditions with bus PTs, SOTFR must be disabled to prevent shutting off SOTF elements once the line breaker opens and the bus PT voltage becomes healthy.

It is rare to require nondirectional elements for dependability when closing a breaker in bus PT applications. Consider a case in which there has been a bus fault at the follower station, and there is tapped load on the line between the leader and the follower. The leader breaker is closed to begin the process of re-energizing the follower substation bus. The next step is to close the follower, which is utilizing bus PTs, to re-energize the bus. If there is a bus fault still present when the follower breaker is closed, you can enable nondirectional elements to trip the follower quickly to prevent the leader from opening and dropping load unnecessarily on the line. If the bus at the follower station has bus differential protection, you do not need to enable any special protection in this case.

This special case falls outside of traditional SOTF protection because the fault in question is in the reverse direction. Therefore, directional overreaching zones do not operate. Also, a 50P element supervised by 27P only operates for three-phase faults. This unique condition requires either auxiliary logic outside the scope of traditional SOTF or the installation of a bus differential.

E. High-Speed Reclosing

To enable high-speed reclosing, each terminal must trip initially on a communications-assisted tripping scheme. Once that happens, each terminal is reclosed with a very small delay to restore the system quickly. During these operations, large inrush currents resulting from breaker closing angles and line charging are possible. Because the closing of each terminal is near the same time, each terminal must follow NERC loadability requirements. If you use 50P for SOTF protection, supervise it with 27P. If you need additional security, you can add a time delay of 1–1.5 cycles to the 50P element to effectively remove the transient overreaching effects from (27P AND 50P) (SOTF) when closing a breaker as shown in Fig. 16. The nondirectional distance element allows the relay

user to define a settable reach that is immune to these switching transients with no need for a time delay.

VII. SUMMARY AND CONCLUSIONS

SOTF protection is essential for maintaining dependability for close-in three-phase faults when energizing a line with line potentials. Dependability and speed are closely related for three-phase faults during SOTF. Although a directional distance element does not operate for a zero voltage condition, it can operate very slowly for three-phase faults that produce less than 10 percent nominal voltage. The operation could be slow enough that remote backup zones clear the fault. While safety grounds at the relay location are often considered the worst case for dependability, three-phase faults away from the substation caused by storms, vehicle crashes, or other serious events expand the zone of required dependability and speed outside the substation, particularly for high SIR systems.

When using a 50P element for SOTF protection, take care to ensure dependability under single contingency conditions.

SOTF security is necessary so you can successfully energize a line under non-fault conditions. Tripping elements must remain secure when you close the leader breaker for a line with high line charging current and/or multiple tapped loads. If SOTFR is used and is successful, the follower breaker does not have SOTF elements enabled when it closes, removing security concerns for load transfer across the line.

In this paper, we discussed plotting the 50P, 27P, (27P AND 50P) (SOTF), and nondirectional distance elements in the impedance plane to examine security when energizing the leader breaker. Of these options, the nondirectional distance elements allow greater control over security by allowing the user to reduce reach to minimize exposure to line charging current and tapped load conditions.

We discussed other considerations regarding SOTF including SOTF window time, enabling SOTF, SOTFR considerations, installations with bus PTs, and high-speed reclosing considerations.

To optimize SOTF settings to balance dependability security, and speed we discussed the following:

- You can use 50P, set to 1.5 times pickup, for an end-of-line three-phase fault with the remote breaker open and with the strongest source behind the relay out of service (worst-case single contingency). If this setting is below tapped load or line charging current, use 27P supervision.
- It is a good idea to supervise 50P with 27P (and this is required in some tap load/high line charging current conditions), even if you use SOTFR. Set the value of 27_{PU} no lower than 0.1 pu and no higher than 0.7 pu. This paper provides (13) to allow you to set 27_{PU} such that it still allows dependable operation for three-phase faults along the line during line energization.
- A sensitively set 50G has security concerns upon closing into a line during SOTF. Give careful consideration to determining if 50G provides any reasonable benefit by its inclusion in SOTF.

- Enabling overreaching directional phase and ground distance elements without time delay during SOTF conditions guarantees fault coverage for unbalanced fault types. This also allows fast clearing for all faults along the line.
- A nondirectional distance element, which is dependable even when closing into a close-in three-phase fault, allows significant simplification of settings for SOTF protection. No additional consideration for faults under single contingency conditions are required; just set an overreaching forward reach and a reverse reach that is secure for line charging and tapped load conditions. The security of a nondirectional distance element does not vary with system conditions, and the element operates fast for all fault types within the reach.

VIII. REFERENCES

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IX. BIOGRAPHIES

Rohith Poduval received his B.E. in Electrical and Electronics Engineering from Anna University, Chennai, India, in 2010 and M.S. in Electrical Engineering from University at Buffalo - The State University of New York in 2013. Upon graduation, he joined North American Protection and Control as a Field Engineer. His responsibilities included high voltage substation commissioning and relay testing. In 2015, he joined Northern Indiana Public Service Company as a Power System Protection Engineer. His responsibilities include protection and control design for generation, transmission, and distribution stations. Rohith is a registered professional engineer in the state of Michigan and a member of IEEE.

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

Sujay Dasgupta received his B.Tech in Electrical Engineering from Nirma University, Ahmedabad, India, in 2017, his M. Eng in Energy Systems in 2018, and his M.S. in Electrical & Computer Engineering from University of Illinois at Urbana Champaign in 2020. He has had research experience in power system protection and stability analysis, cybersecurity, and switchgear design. He joined Schweitzer Engineering Laboratories, Inc. in 2019 as an application engineering intern. He is a student member of IEEE.