

# Single-Pole Operation in the Distribution Substation: Benefits, Challenges, and Solutions

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**Abstract**—Utilities have used single-pole tripping, reclosing, and lockout strategies for many years across distribution systems. The broad adoption by utilities of advanced recloser controls and independent pole reclosers, which can operate poles independently to reduce the number of customers that are impacted by non-three-phase faults on the distribution system, has increased reliability metrics.

While prominent out on the distribution system, bringing single-pole operation inside the distribution substation fence has historically been challenged by an absence of primary equipment and protective devices capable of single-pole operation. In some cases, utilities have applied reclosers in lieu of substation feeder breakers; however, this approach often brings tradeoffs, such as different operational procedures, additional control hardware, and design constraints. American Electric Power is an example of a utility that has experience implementing selective single-pole operations both outside and inside their substations, using reclosers where applicable.

With advancements in distribution feeder breakers and relays, single-pole operation functionality for distribution substation applications is no longer restricted by equipment capability. American Electric Power is, therefore, pursuing further evaluations to see how this technology could add additional benefits to their system. This paper discusses the benefits of single-pole operation throughout the distribution system, considerations for implementation of this protection philosophy, and the impact these new technologies may have within modern distribution substations.

## I. INTRODUCTION

Solidly grounded distribution systems prevalent within many countries, such as USA, Canada, Australia, and those in Latin America, often have a mix of single-phase and three-phase loads tapped off utility feeders [1]. In fact, there are also numerous single-phase distribution laterals that have all the loads connected to just one of the phases. Unlike transmission systems, which may be challenged with overload, stability, critical three-phase loads, and wide area protection coordination, these distribution systems can often allow for temporary and sometimes permanent operation with only one or two phases energized [2] [3].

Notably, most electrical faults in three-phase power systems involve one or two of the three phases [3]. The combination of these conditions calls attention to the fact that if single-phase protective operations can be performed, customers on unfaulted phases can statistically remain unaffected by most system faults.

The reliability of an electrical power distribution system is calculated based on the average number of customers

interrupted, the average duration of service interruption, or a combination of the two [4]. Utilities strive for higher service reliability, which is measured using the standard reliability indices [5]. Tripping all three phases for a fault on one or two phases in a distribution system leads to an unnecessary interruption of power to customers connected on the healthy phase(s). This interruption increases the number of customers impacted, which causes a decrease in reliability.

Temporary faults are more common than permanent faults in overhead lines. Therefore, to avoid a prolonged interruption of customers, utilities often make use of automatic reclosing following a trip performed by a protective relay. If the fault is temporary, automatic reclosing restores power within a few seconds. The use of automatic reclosing following a trip initiated by a protective relay is common in transmission as well as distribution systems [6] [7].

To reduce the number of customers interrupted for a temporary fault, single-pole tripping (SPT) is also used if the primary equipment, such as a circuit breaker or recloser, allows single-pole operation. By using SPT, only the customers on the faulted phase see an interruption, while the customers on the healthy phases are not interrupted at all.

If the fault is permanent, the circuit breaker or recloser goes into lockout mode after the set number of reclosing attempts has been exhausted. The lockout mode can either be three-pole lockout (TPLO) or a single-pole lockout (SPLO). However, TPLO or SPLO can be used on distribution systems depending on load configuration.

SPLO improves the reliability of the distribution system greatly compared to TPLO. The response time to restore power after a lockout can be several hours, since a utility crew must locate the fault, clear it, and then initiate a manual close. SPLO prevents an outage to customers on the healthy phases during that time [5].

Distribution systems can have a mix of single-phase and three-phase loads. In fact, there are also single-phase distribution laterals that have all the loads connected to just one of the phases. Advanced digital protection devices can adapt to unbalanced loads by setting protection elements to accommodate for the unbalance so, in practice, unbalanced loads do not significantly affect protection [8].

For this reason, it is a common practice at utilities, such as American Electric Power (the utility), to have single-pole-capable primary equipment, such as reclosers capable of SPT/SPLO, paired with advanced recloser controls [8].

While the use of reclosers solves the problem outside the substation fence, for faults between the substation feeder breaker and the first recloser, there is still a problem of three-pole trips for single-phase faults. When a permanent single-phase fault occurs in the line segment shown in Fig. 1, all the customers on the feeder would be disconnected due to TPLO at the feeder breaker.

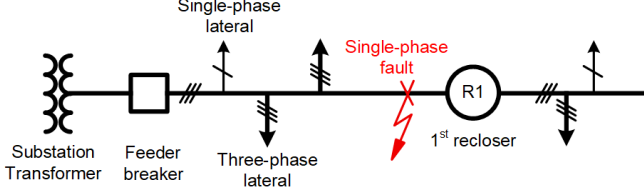


Fig. 1. Typical distribution feeder.

To overcome this, the utility has applied reclosers instead of circuit breakers in numerous substation feeder breaker positions where design criteria have allowed it. While this application works well for most cases, the challenge for utilities is that reclosers have different operating procedures, come with lower fault-interrupting and load-current capabilities, and need additional hardware compared to circuit breakers [9]. The ideal solution to this problem is to have a feeder relay and circuit breaker capable of SPT/SPLO that functionally align with the design and operation of the recloser. The consistent function and operational interface eliminate the need for engineers and technicians to learn two different operational procedures.

In this paper, we present the benefits of applying SPT/SPLO at the feeder breaker using various reliability indices [5], followed by considerations to be made before the application of SPLO.

Although SPLO has a great benefit to reliability, there are also challenges associated with this approach (and sometimes SPT as well), including: use/security of sequence components-based elements to gain fault sensitivity, load configuration considerations (delta transformers, three-phase customers, etc.), and evolving faults (exacerbated by slow curves and additional reclose attempts). We also discuss some of the protection challenges during SPLO and the protection schemes suited for such.

## II. BENEFITS OF SPT/SPLO AT THE SUBSTATION FEEDER BREAKER POSITION

Distribution system reliability is critical to utilities since it accounts for approximately 40 percent of the cost to deliver power [10]. Utilities use reliability indices to quantify the reliability of their networks. Two of the commonly used reliability indices are:

1. System Average Interruption Duration Index (SAIDI)—indicates the time of interruption for the average customer.
2. System Average Interruption Frequency Index (SAIFI)—indicates how often the average customer experiences a sustained interruption.

SAIDI and SAIFI are calculated mathematically using (1) and (2), respectively [5].

$$SAIDI = \frac{CMI}{N_T} \quad (1)$$

$$SAIFI = \frac{CI}{N_T} \quad (2)$$

where:

CMI = Total number of customer minutes interrupted.

$N_T$  = Total number of customers served for the area.

CI = Total number of customers interrupted.

While it is intuitive that the use of SPLO at the feeder breaker will improve the reliability indices, the actual improvement depends on the loads connected and the location of the fault.

For the example in Fig. 2, which is derived from Fig. 1, consider a Phase A fault between the feeder breaker and the first recloser with an interruption duration of 60 minutes.  $N_T$  is calculated using (3).

$$N_T = 50 + 60 + (80 + 80 + 70) + 30 + (50 + 40 + 40) = 500 \quad (3)$$

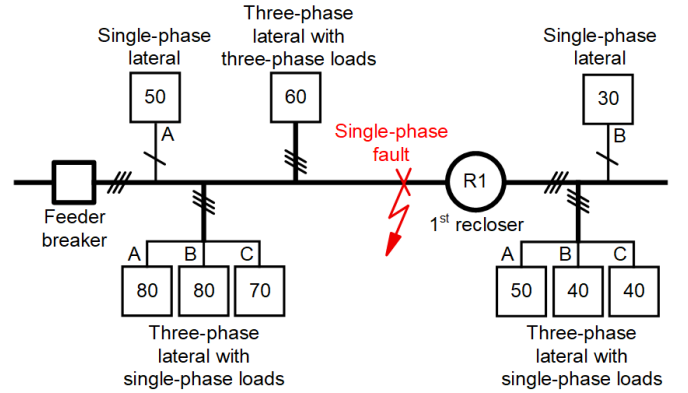


Fig. 2. Load and number of customers per phase for a typical distribution feeder.

If the feeder breaker only supports TPLO, the resultant reliability indices for this Phase A fault event are calculated as shown in (4), (5), (6), and (7):

$$CMI = N_T \cdot \text{duration} = 500 \cdot 60 = 30,000 \quad (4)$$

$$SAIDI = \frac{CMI}{N_T} = \frac{30,000}{500} = 60 \quad (5)$$

$$CI = N_T = 500 \quad (6)$$

$$SAIFI = \frac{CI}{N_T} = \frac{500}{500} = 1.00 \quad (7)$$

If the feeder breaker supports SPLO (and it is enabled), the resultant reliability indices for this Phase A fault event are calculated as shown in (8), (9), (10), and (11):

$$CMI = (50 + 80 + 50 + 60) \cdot 60 = 14,400 \quad (8)$$

$$SAIDI = \frac{CMI}{N_T} = \frac{14,400}{500} = 28.8 \quad (9)$$

$$CI = 50 + 80 + 50 + 60 = 240 \quad (10)$$

$$SAIFI = \frac{CI}{N_T} = \frac{240}{500} = 0.48 \quad (11)$$

Note that for the calculations shown in (8), (9), (10), and (11), in addition to the load on Phase A being interrupted, the three-phase loads are also interrupted. This interruption is caused either by the customer-provided protection devices locally to those loads, which detect the pole-open condition at the feeder breaker and isolate the three-phase load, or by a communications-assisted scheme that trips the local protection for the three-phase loads. There are numerous methods of communications-assisted tripping, but in this scenario for a SPLO condition, a simple direct transfer trip (DTT) is sufficient. If the method selected to isolate the three-phase loads is DTT, the upstream breaker relay would have to send a DTT to all three-phase loads. However, there are additional considerations to this operation. The breaker relay sends a DTT to the three-phase loads on the assertion of the SPLO. The success of the following single-pole reclose determines if the three-phase load can be brought back online or not. Therefore, the DTT can be followed by a remote close to the three-phase load for successful single-pole reclose operations. Of course, the breaker relay must support the functionality to communicate the DTT and remote close.

From (5) and (9), the SAIDI reduces from 60 minutes of interruption per average customer for a TPLO to 28.8 minutes of interruption per average customer for SPLO. Similarly, comparing (7) and (11), the SAIFI with SPLO enabled reduces from 1.00 to 0.48.

Reliability indices calculated with SPLO for a fault on Phases B and C can similarly be calculated and are shown in Table I.

TABLE I  
SAIDI AND SAIFI WITH SPLO AT FEEDER BREAKER

|       | Phase A fault | Phase B fault | Phase C fault |
|-------|---------------|---------------|---------------|
| SAIDI | 28.8          | 25.20         | 20.40         |
| SAIFI | 0.48          | 0.42          | 0.34          |

### III. FUNDAMENTALS OF SINGLE-POLE RECLOSING IN DISTRIBUTION SYSTEMS

#### A. Reclose and Lockout Modes Available

When applying SPT-capable breakers and relays, reclosing and lockout modes must be considered. The following variations are available in SPT-capable breakers and relays.

##### 1) *Three-Phase Trip, Three-Phase Reclose, Three-Phase Lockout*

This mode must be used if the feeder breaker is only a three-phase-capable device. For this variation, the breaker trips, recloses, and locks out three phases regardless of the fault type. This prevents momentary or sustained single phasing of three-phase loads. This method is very common at the distribution feeder breaker and is the most straightforward from an implementation perspective as all faults at all locations result in the same protection logic being executed.

For example, for a Phase A fault, all three phases trip and reclose. If the fault persists even after the reclose attempts are exhausted, all three phases lock out. It should be noted that all

protection, reclosing, and lockout logic is the exact same for all fault types.

##### 2) *Single-Phase Trip, Single-Phase Reclose, Three-Phase Lockout*

This mode operates independent poles for trip and reclose operations but locks out all three poles for any permanent fault on the system. This method does require that each phase be configured to support the single-pole trip and single-pole reclose. Simply put, the protection and reclosing logic must be configured three times for this method to operate as designed. This method is suited for loads that can tolerate momentary single-phase conditions that are present for less than the open interval time of the reclosing logic, but the system would not remain stable for a permanent single-pole-open condition.

For example, for a Phase A fault, Phase A trips and recloses. If the fault persists even after the reclose attempts are exhausted, all three phases lock out. This requires that the protective relay support individual phase trip equations (TRIP A/B/C), independent phase reclosing logic (Initiate Reclosing A/B/C, Supervision A/B/C, Open Interval Timing A/B/C, Reclose A/B/C, Reset Timing A/B/C), and one three-phase lockout equation. There are numerous intricacies of reclosing logic that are not included in the list of settings above. The intent of the list above is to highlight the typical settings that must be configured for single-pole reclosing to operate.

##### 3) *Single-Phase Trip, Single-Phase Reclose, Single-Phase Lockout*

This mode operates independent poles for trip, reclose, and lockout operations. It requires similar logic to that described in the previous section (Section III.A.2), with the exception that the lockout logic is on a per-phase basis. It is suited for systems that have single-phase loads connected and the stability of the system is not compromised by operating with one or two poles permanently open [11].

For example, for a fault involving Phases A and B, those two phases will trip and reclose. If the fault persists even after the reclose attempts have exhausted, those two phases lock out while customers on Phase C are still connected. This is different from a transmission system, where a multiphase fault would always result in a three-phase reclose trip, three-phase reclose, and three-phase lockout.

##### 4) *Single-Phase Trip, Single-Phase Reclose, Single-Phase Lockout Evolving to Three-Phase Lockout if Two or More Phases Have Tripped*

This mode operates independent poles for trip, reclose, and lockout operations. The same settings configuration as Section III.A.3 is used. However, for a fault involving two phases or two separate phases to ground faults at different times, all the three phases are locked out. The choice of using this mode as opposed to allowing only two phases to lock out with the third phase still connected is based on the practice of the utility [11]. There are some intricacies to implementing this scheme. For a phase-to-phase fault, the individual phase automatic reclosers will sequence through their shots at the same time.

For example, if there is an AB fault, the A and B automatic reclosers will be on the same shot and thus drive to lock out at the same time. However, if there are two phases faulted at different times (AG fault followed by a BG fault), the shot counters will not be the same, as one phase is locked out and the other may just be starting its shot sequence. In this case, it may be desired not to attempt a reclose and immediately drive to three-phase lockout. The desired behavior is achievable via programmable logic. This method is suited for systems that only have single-phase loads connected.

#### B. Differences in Implementing Single-Pole Tripping and Reclosing in Distribution and Transmission Systems

While the fundamentals of single-pole tripping and reclosing apply regardless of transmission or distribution systems, their application is not the same. The differences arise due to the power system requirements to operate at each voltage level.

Transmission systems are designed to always operate as three-phase systems to ensure stability, whereas distribution systems consisting only of single-phase loads may operate as single-phase systems indefinitely, if needed, since this greatly improves the reliability indices previously discussed without impacting system stability.

1. In transmission systems, the three-phase trip, three-phase reclose, three-phase lockout or single-phase trip, single-phase reclose, three-phase lockout mode is used, since a sustained single-phase lockout would result in unbalanced currents, which might have damaging effects on generating units [3] and the rest of the power system [7].
2. Transmission systems also typically use only one single-phase reclose attempt, unlike distribution systems that can have multiple single-phase reclose attempts. If the single-phase reclose attempt in a transmission system is unsuccessful, it is followed by a three-phase trip and a three-phase reclose [7].
3. If a breaker reclosing failure occurs in transmission systems due to breaker failure, the pole-discrepancy logic trips the other two poles [3]. However, distribution systems can continue to operate in the configuration with one of the poles open and the other two closed.

#### C. Sequence Coordination Using Shot Counters

Reclosing relays use shot counters to remain in step with downstream devices and prevent operation of overreaching elements when a fault occurs beyond the downstream device. This logic requires that feeder relays and recloser controls increment their shot count for downstream faults, even if they did not issue a trip. Ensuring that devices protecting a distribution are aligned on a shot count is required because typical applications require both fast and delay curves to be implemented. Depending on the preference of a utility for either fuse saving or fuse blowing, a different time-overcurrent curve is selected based on the shot count.

For example, a utility may choose to use a fast curve for Shots 1 and 2 to prevent downstream fuses from blowing, and then a delay curve for Shots 3 and 4 to clear a fault with a downstream fuse. For this scheme to operate as designed, all feeder relays and recloser controls must be using the same time-overcurrent curve settings, which are driven by the shot count. To allow the use of either the three-phase or single-phase modes, separate shot counters are used for each [12].

#### D. Cold Load Pickup

After a prolonged lockout condition, the load diversity of the open phase is lost. When the fault is cleared and the pole is closed after a significant amount of time, the cold load inrush current might be greater than the overcurrent element pickup values and cause an incorrect operation. The logic to enable cold load must be implemented on a per-phase basis when using SPT and SPLO. Otherwise, the remaining phases are being desensitized unnecessarily. When cold load logic is active, the fast curves can be disabled, and the delay curves can be desensitized on the affected phase [13].

#### E. Second-Harmonic Blocking

Transformers draw an inrush current when they are energized. Following a trip and reclose, all the transformers are simultaneously energized. This energization could result in the inrush current being greater than the overcurrent element pickup values and cause an incorrect operation. This system phenomenon is common in distribution systems because of the number of pole-mounted transformers. One of the signatures to identify transformer inrush current is the presence of second harmonic. If the second-harmonic current as a percentage of the fundamental frequency is above a preset threshold value, the operation of overcurrent elements can be blocked [14]. Again, this logic must be implemented on a per-phase basis when SPLO has been implemented because the locked-out phase is the only phase that will detect second-harmonic current and the only phase that should be blocked from operating during this condition.

### IV. SYSTEM OPERATION CONSIDERATIONS AND SOLUTIONS FOR APPLYING SPLO

SPLO significantly improves reliability indices, as seen from the example in the previous section, but there are some considerations to be made before its application.

#### A. System Configuration and Load Connection

Consideration: Three-phase distribution systems can either be in a three-phase three-wire or a three-phase four-wire configuration (three-phase wires and a neutral wire).

Three-phase three-wire distribution systems only contain three-phase loads or phase-to-phase loads due to the absence of a neutral. Therefore, in such configurations, the use of SPLO will not be beneficial because the load would need to be disconnected even if one phase locks out.

On the other hand, three-phase four-wire distribution may contain single-phase or three-phase loads. If the network contains only single-phase loads, using SPLO would be the most beneficial since the customers on the unfaulted phases are still being served by the utility. If the network contains a mix of single-phase and three-phase loads, SPLO may be beneficial if the three-phase loads can be isolated from the system via local protection.

### B. Three-Phase Motor Loads

**Consideration:** Motor loads are one of the three-phase loads that are susceptible to damage during open-phase conditions. The theoretical maximum currents drawn by motor loads during an open-phase condition could be as high as 1.732 pu. Additionally, during an open-phase condition, the resulting negative-sequence current would produce a magnetic flux rotating in the opposite direction to the rotor, which results in a double-frequency current flowing in the rotor. This may result in motor damage due to excessive heating [15].

**Solution:** Customer-provided protection devices for motors usually have an unbalance detection based on phase current magnitude differences, negative-sequence currents, or negative-sequence voltages [6]. Such motor protection usually converts detected SPLO unbalance on the primary system to an effective TPLO/isolation of the corresponding motor loads.

Thus, greater consideration can be given to having the rest of the distribution feeder primary system continue with an SPLO condition, increasing reliability for more single-phase customers.

### C. Cable Capacitance

**Consideration:** Feeder breaker SPLO (like in Fig. 3) can result in ferroresonance on a distribution circuit, depending on circuit capacitance, transformer bank loading, etc. [15]. Ferroresonance may also occur when all three poles are closed; however, from field experiences, single-phase switching in distribution networks is known to be one of its common causes [16].

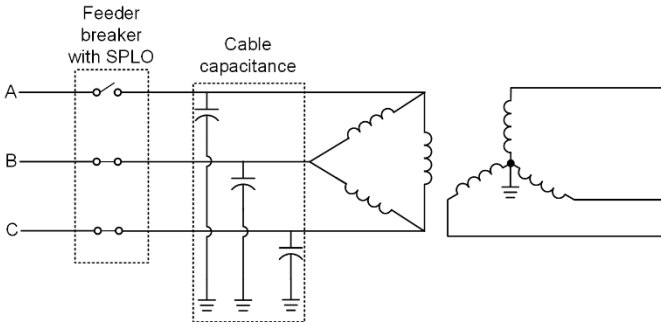


Fig. 3. Distribution network with a cable section.

Ferroresonance is a nonlinear resonance that can produce equipment-damaging overvoltage, which causes transformers to overheat and stresses the insulation for any connected equipment. Like linear resonance, ferroresonance is caused by the interaction between the circuit capacitance and inductance.

However, unlike linear resonance, the inductance involved is the nonlinear core of the transformer. Therefore, ferroresonance is difficult to predict. It is sensitive to parameters such as transformer saturation voltage, remanent flux in the transformer core, the point on wave where the voltage is applied, and the load connected [17].

However, it should be noted that not all circuit configurations cause ferroresonance and a detailed system study is needed to understand if the network under consideration is susceptible to ferroresonance.

**Solution:** During ferroresonance, the currents flowing in the closed phases are rich in harmonics and the voltage on the load side of the open phase (see Fig. 3) can be more than the nominal voltage. Logic can be configured to detect such conditions and trip the feeder breaker to TPLO.

### D. Distributed Energy Resources

**Consideration:** Distributed energy resources (DERs) in a distribution system increase settings complexity for feeder relays as opposed to traditional radial feeders with no DER. This ranges from determination of fault direction to changes in fault current levels. Other challenges are the ability of the DER to detect a feeder breaker SPLO condition (an effective islanding condition for the DER) and, likewise, the ability of the feeder breaker relay (which created the feeder breaker SPLO condition) to detect the continued presence of a DER on the distribution system.

IEEE 1547.2-2023 [18] requires a DER to detect an unintentional island and cease to energize within 2 seconds. While this is possible in most cases, the protective devices at the point of common coupling can also detect this condition to disconnect the DER [19].

Consider a feeder with a DER downstream of a feeder breaker SPLO condition (see Fig. 4). The power output of the DER is  $P_G$ . The total feeder load is cumulatively represented as  $P_L$ .

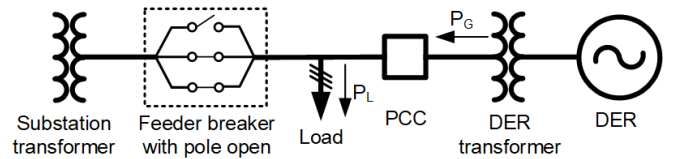


Fig. 4. Feeder breaker with pole open in a feeder with DER and load.

When there is significant power exchange with the grid due to a mismatch between  $P_G$  and  $P_L$ , islanding can be detected by the DER due to the change in voltage on the SPLO phase. However, when  $P_L/P_G$  is close to 1, the detection of an islanding condition by the DER is difficult [20].

**Solution:** Bring feeder breaker load-side voltages into the feeder breaker relay to help detect the continued presence of a DER on the distribution system after a feeder breaker SPLO condition. In the absence of a DER, the load-side voltage on the SPLO phase would be near zero. With the DER still present, the load-side voltage on the SPLO phase would be close to nominal for  $P_L/P_G$ , close to 1.

## V. SYSTEM PROTECTION CONSIDERATIONS AND SOLUTIONS FOR APPLYING SPLO

### A. Sequence Components-Based Protection

Consideration: If the feeder is heavily loaded, using SPLO might cause an unbalance greater than the pickup value for the ground overcurrent element [21]. For example, consider a feeder with a nominal current of 500 A on each phase. If the feeder is loaded to 400 A on each phase (80 percent of nominal current) when a SPLO occurs, the ground current can be calculated as shown in (12).

$$\begin{aligned} I_G &= 3I_0 = I_A + I_B + I_C \\ I_G &= 0\angle 0^\circ + 400\angle -120^\circ + 400\angle 120^\circ \\ I_G &= 400\angle 180^\circ \text{ A} \end{aligned} \quad (12)$$

It should be noted that the magnitudes and angles of the closed phase currents in (12) are used as an example. There might be some deviation in the magnitudes and angles after a pole is opened; however, the deviation is not very significant. Also, the phase angles considered in (12) only apply when all the loads are single-phase.

If the ground element is set to pick up at 250 A (50 percent of nominal current), the SPLO condition can cause the ground element to inadvertently operate.

On the other hand, if the current flowing is 100 A (20 percent of nominal current), the ground current is only 100 A, which is not enough for the ground element to operate. This example highlights that single-pole operations must consider both the condition when all poles are closed as well as when one or two poles are open.

Solution: Microprocessor relays usually support multiple instances of the ground element. Each of these instances use a qualification condition to choose which instance should operate based on the pole-open condition.

For example, if the relay supports two different instances of the ground overcurrent element, then the qualification logic for the sensitive instance can be set to check that a pole-open condition does not exist. The pickup value for this element can be set just above the maximum unbalance allowed in the system with all three poles closed.

The second instance of the ground overcurrent element can be desensitized by setting its pickup value equal to the phase overcurrent element. This instance would only be allowed to operate when a pole-open condition is detected.

In the example from (12), if the maximum unbalance allowed in the system with all three poles closed is 25 percent, the threshold for the sensitive ground overcurrent element can be set to 125 A (25 percent of 500 A).

### B. Coordination With Downstream Devices

Consideration: Most protective devices downstream of the feeder breaker are recloser controls. These recloser controls block schemes that may operate incorrectly during open-phase conditions. For detecting open-phase conditions, the recloser controls can either use voltage-based logic or contact-based logic when the current is less than a predetermined threshold.

A voltage-based pole-open detection logic works when the voltage is less than a predetermined threshold. The contact-based logic uses the normally open and sometimes the normally closed auxiliary contacts of the circuit breaker or the recloser to detect a pole-open condition.

The contact-based logic only works when a pole opens at the recloser that performed the operation, since the contact statuses of the upstream devices will not be available for the downstream devices to use, unless there is a means of communications between the recloser sites.

Generally, a feeder relay and recloser control that provide the same set of features and functions allow for logic to be implemented in each device the same way. This simplifies settings configuration and harmonizes operations between the two devices. It is not a requirement that this be the case, but it allows for more straightforward coordination of protection.

Solution: Using a combination of the voltage-based pole and contact-based pole-open detection methods can allow the detection of upstream pole-open conditions in addition to the primary equipment pole-open condition. This will prevent inadvertent operation of protection elements on downstream protective devices.

## VI. CONCLUSION

In this paper, we present an overview of applying single-pole trip and lockout to feeder breakers and the various considerations that should be made before using this strategy.

One of the benefits of SPLO is the improvement in reliability indices based on the number and type of customers between the feeder breaker and the first recloser. Another advantage is the elimination of reclosers from the substation, thus allowing higher fault and load current using circuit breakers and feeder relays at the substation.

We also discuss some considerations utilities would need to make for the application of single-pole trip and lockout to feeder breakers. However, these challenges can be overcome using microprocessor-based relays.

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