

Comparison of Nontraditional Distribution Protection Schemes and Coordination Methods for FLISR-Enabled Distribution Networks

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Comparison of Nontraditional Distribution Protection Schemes and Coordination Methods for FLISR-Enabled Distribution Networks

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Abstract—Improving distribution system reliability commonly involves increasing the density of reclosers to minimize end user interruptions and implementing fault location, isolation, and service restoration (FLISR) systems to restore service quickly after permanent faults. As utilities deploy more protection devices on their circuits, new recloser protection and coordination schemes have emerged to address the challenges posed by traditional coordination methods when many devices are installed in series. This paper evaluates three nontraditional schemes to help utilities identify the most effective approach for their distribution systems: recloser voltage-guided reclosing, recloser communications-assisted tripping, and fault-reporting switches, which may or may not be reclosers. The comparison considers scalability factors such as system size, clearing times, and scheme complexity; hardware and infrastructure needs including equipment ratings, relay capabilities, and communication media; end user impacts both with and without FLISR integration; and associated safety considerations.

I. INTRODUCTION

In this paper, three nontraditional distribution-coordination methods are evaluated on their impact on standard distribution system reliability metrics, as well as on practical considerations for implementation and ownership. These schemes are primarily considered when operating alongside a wide-area fault location, isolation, and service restoration (FLISR) system. The behavior of these schemes under the contingency scenario of a loss of communication to the FLISR system is also discussed.

For the purpose of this paper, the three coordination methods being discussed are referred to as recloser voltage-guided reclosing (VGR), recloser communications-assisted tripping

(CAT), and fault-reporting switches (FRS). VGR is defined in detail in [1]. In the industry, this scheme has been referred to as non-communications-based high-density distribution coordination. CAT is also referred to as high-density distribution coordination and is defined in detail in [2]. The terms high-density distribution coordination and non-communications-based high-density distribution coordination are not used in this paper since high-density distribution coordination is an objective rather than a specific method, and all three of the schemes are designed to meet that objective.

II. RELAYING SCHEME DEFINITIONS

This section provides a brief overview of the three schemes evaluated in this paper: VGR, CAT, and FRS.

A. VGR

A defining aspect of VGR is its use of logic to control and delay a traditional reclosing sequence. As such, the scheme requires fault-interrupting recloser hardware and a control with user-configurable logic capability.

The scheme allows multiple reclosers to have identical protection and coordination set points and relies on logic within the reclosing equation to ensure that only the proper device trips during reclose attempts. For the purposes of this paper, devices in a VGR scheme with identical protection set points are referred to as a coordination group. Fig. 1 shows an example of how VGR devices are separated into coordination groups. The scheme performs upstream protection isolation operations fully without requiring communication between reclosers or with a FLISR system.

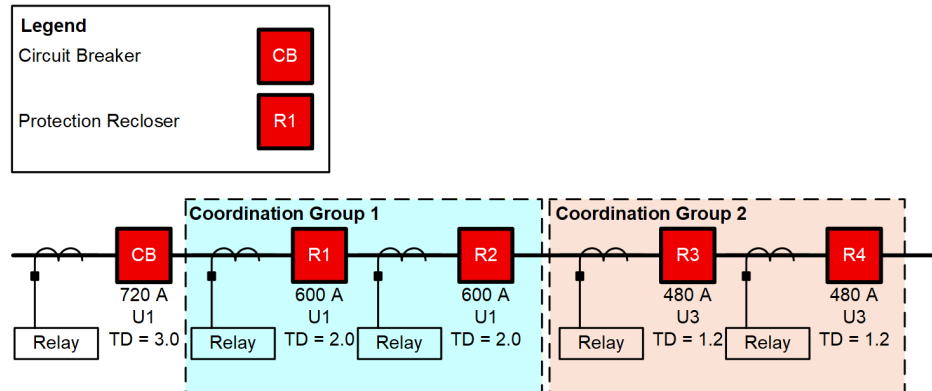


Fig. 1. Example Time-Overcurrent (TOC) Coordination Groups

B. CAT

A defining aspect of CAT is that the scheme uses identical or nearly identical low-set overcurrent elements with a definite time-delay in all devices. Assertion of the overcurrent element is sent as a blocking signal to neighboring devices over a high-speed communications network. If a device receives multiple blocking signals, it is not the device nearest to the fault and therefore delays tripping. If sufficient blocking signals are not received before the definite delay occurs, the device trips.

The scheme requires all devices to be fault-interrupting reclosers with controls that have user-configurable logic and high-speed communications capability. It also allows all devices to have identical protection set points and logic, except for devices at the system edge, which may have to coordinate with non-CAT protection devices. Depending on the communications protocol used, each device may have unique communications settings for the high-speed protocol used.

CAT requires high-speed communications capable of reliably meeting the desired clearing time. If communications are lost, devices will use a backup protection scheme, such as traditional TOC coordination or a VGR scheme. High speed is relative to the required tripping time and does not necessarily follow the strict requirements of a transmission system. Therefore, it is encouraged to examine the reasoning behind the desired clearing speed when exploring this option.

Typical clearing times for CAT schemes are in the range of 50 ms, but if a slower communications speed is the only available option, then slower times may be allowed. When slowing the clearing time in a CAT scheme, coordination with equipment damage curves is the primary consideration, particularly on systems with older equipment and higher fault-duty levels. The total clearing time of the CAT trip (protection time plus communications delay) should be carefully considered and compared with common equipment damage curves.

Reference [2] originally used a definite-time element for the fast trip; however, the utility mentioned in [2] has since changed to a TOC curve to provide better coordination with fuses.

C. FRS

FRS is the use of fault detection or reporting at remotely operable switching devices, alongside traditionally configured and coordinated reclosers, to provide a high density of devices for FLISR to operate following traditional protection reclosing and lockout. For the purposes of this paper, an FRS scheme is defined as the combination of FRS between traditionally coordinated circuit breakers (CBs) and reclosers while an FRS device is defined as a single FRS. In the simplest cases, an FRS scheme may consist of only a traditionally coordinated CB with one or more downstream FRS devices.

A defining aspect of FRS is that devices are located between traditionally coordinated CBs and reclosers. Consequently, this scheme exists alongside traditional distribution coordination. FRS devices are operated only while the relevant line section is de-energized. As such, FRS devices are not required to be fault-interrupting-rated or load-interrupting-rated to participate in the

scheme. However, if cost allows, it is recommended that the interrupting device use the same model as the fault-interrupting reclosers. This allows the FRS device to be reconfigured as a protective device as the feeder evolves over time or when temporary protection is needed, such as enabling hot-line tag (HLT).

FRS devices have the necessary hardware and logic to detect and report whether a fault is located downstream of the device. Usually, this can be done with a combination of overcurrent elements used to coordinate with magnetizing inrush current. However, in extreme cases, additional protection elements, such as harmonic blocking, may exist if significant inrush is expected. When full-featured controls are used, the FRS device can also report the faulted phase(s) and magnitude. When controls that support fewer features are used, the device can report a binary fault indication, so the FLISR system knows which zone between isolation devices the fault is located in.

Not indicating on inrush current from upstream reclosing is an important consideration in FRS schemes. An incorrect indication leads to a misidentified zone, which in turn leads to increased end users without power for no good reason. Various solutions exist that involve building step functions using instantaneous overcurrent (IOC) elements or using a fast curve, and supervising either with second-harmonic blocking. The reader should note that anecdotal evidence shows that inrush can vary across regions, likely due to the type of loads connected.

Overcurrent set points in FRS devices are not required to coordinate with protection devices. They must only be set high enough to not assert due to load and low enough to assert for a fault. As such, it is possible that a single set of set points may be applied to all FRS devices on a distribution feeder. For simplicity, it is recommended to set the FRS set points equal to the equivalent phase or ground protection upstream.

FRS devices are intended to assist with further sectionalization following traditional coordination and isolation. After traditional protection occurs and lockout is reached, FRS devices within the traditional protection zone can be used to further isolate the fault location within the zone through FLISR or operator intervention. Without outside intervention from a FLISR system or operator, FRS devices do not perform any isolation or restoration switching.

These devices can be configured as sectionalizers to provide automatic local isolation. This option adds unnecessary complexity when a centralized FLISR system is used because the FLISR system itself acts as a global sectionalizer. However, the FRS devices can be programmed as sectionalizers in a backup mode when the FLISR system is down. Where a centralized FLISR system is not used, it is often more effective to program the FRS devices as sectionalizers so that a fault is isolated locally and automatically, eliminating the need for a manual response.

FRS devices may be configured with alternate protection and coordination set-point modes or protection that can be toggled on and off that provides additional value, such as when instantaneous tripping HLT is enabled. When HLT is enabled, the pickup of the FRS device becomes very important because

the device must be able to function as a normal protection device.

FRS circuits should be configured so that the CB relay provides protection for the circuit backbone. Any downstream reclosers at the head of radial line sections should function as protection devices. This includes the tail end of the backbone. All other switching devices may be FRS devices. See Fig. 2 for an illustration of an FRS circuit.

III. FLISR DEFINITION

For the purposes of this paper, FLISR is defined as a wide-area system that operates after a protection device reports a lockout. In temporary fault scenarios, FLISR performs no actions.

Following a protection lockout, FLISR isolates the faulted zone through opening all devices in the surrounding zone and then restores power to all unfaulted zones. For the purposes of metric impact, FLISR is assumed to operate sufficiently quickly such that the total outage duration is under 5 minutes and is thus considered a momentary outage by IEEE definition [3].

For VGR and CAT, the protection scheme should result in the nearest device upstream of the fault being the protection device, which locks out. Additionally, all devices upstream of that device should remain closed by the time a lockout occurs. Therefore, FLISR will isolate the faulted zone using the first controllable device downstream of the fault followed by restoration of all other downstream zones.

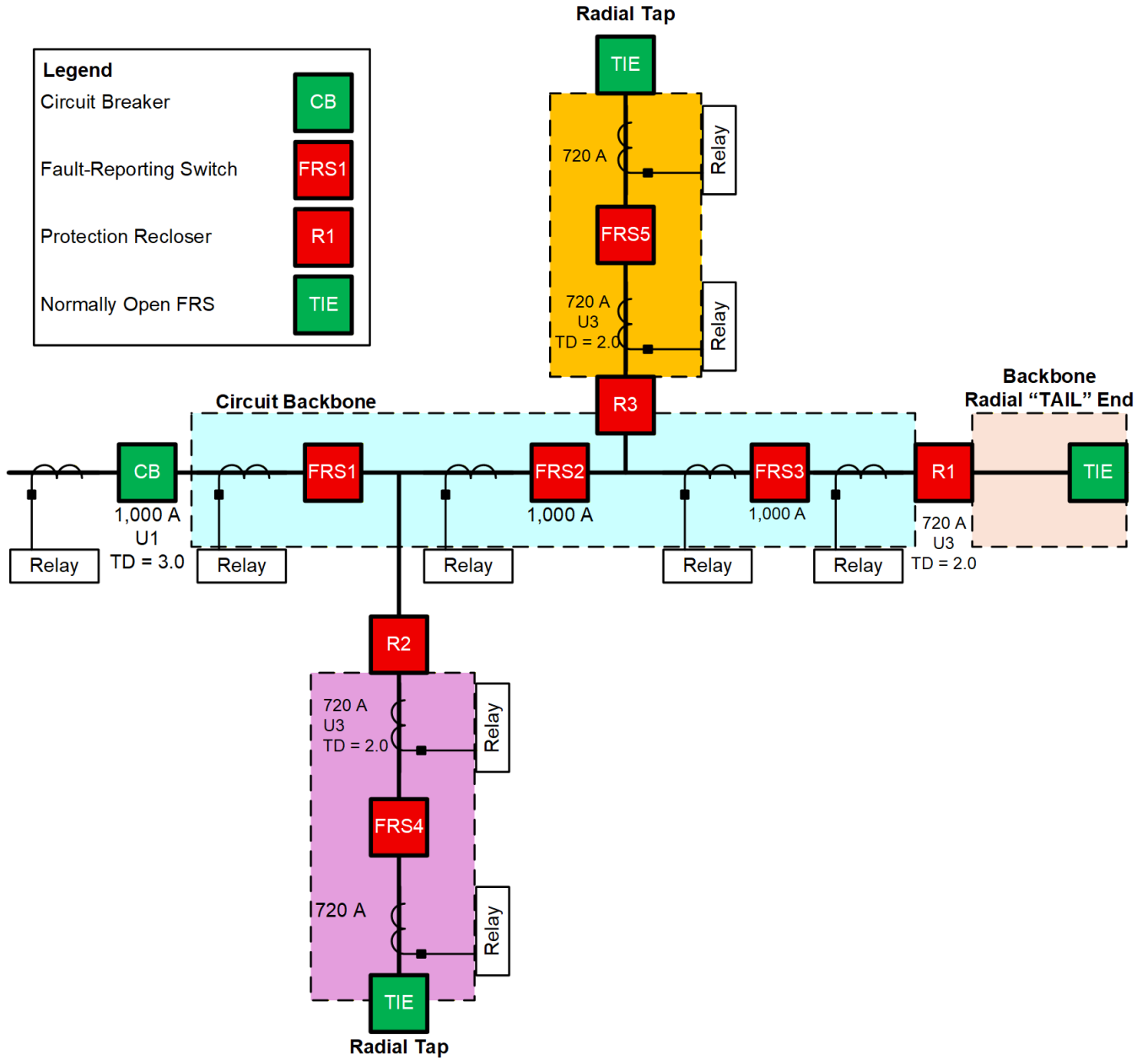


Fig. 2. Example FRS Circuit

For FRS, FLISR plays a more significant role. Under the FRS scheme, the nearest CB or recloser upstream of the fault should be the device that locks out; however, one or more FRS devices may be located between the locked-out device and the fault. As such, FLISR will perform upstream isolation by operating the appropriate FRS device if necessary and then closing the locked-out device. Additionally, FLISR will perform downstream isolation using the first available device downstream of the fault followed by restoration of all other downstream zones. If this sequence is used, FRS devices will only be commanded to open by FLISR when they are electrically de-energized and therefore are not required to interrupt load or fault current. When performing return transfer to reestablish the open point, the open point may be called upon to break load. This is another reason to make all FRS devices mechanically identical to protection devices.

FLISR may also provide the secondary capability of detecting and responding to hanging conductor faults (open-phase conditions). While individual protection devices may be unable to detect these faults due to the lack of fault current, a FLISR system may be able to detect and determine a hanging conductor fault location based on the reported voltages from the monitored devices. When this condition is detected, FLISR may perform fault isolation and service restoration. The capability of this operation will be limited based on the presence or lack of voltage sensing on controllable devices.

IV. PROTECTION SCHEMES CONSIDERED

This section provides a brief overview of commonly applied distribution protection schemes and discusses the potential impacts of the relaying schemes discussed in this paper (VGR, CAT, and FRS) on those protection approaches.

Distribution protection schemes have increased in complexity in recent years due to heightened end user expectations for continuity of service, growing penetration of distributed energy resources (DERs), and the emergence of large end user loads [1]—in particular, data centers with demands that may approach the full ampacity of a feeder conductor, as well as broader electrification trends. This section examines these factors in the context of the schemes under consideration and evaluates their implications for widely used protection and coordination practices on distribution feeders.

Numerous variations of customized protection schemes exist in utility systems; however, a comprehensive evaluation of all possible configurations is beyond the scope of this study. Therefore, this discussion focuses on the protection and coordination impacts associated with the most commonly deployed schemes that closely align with established industry standards and practices.

The distribution protection elements considered in this study are briefly described in following sections. The specific impacts of each relaying scheme on these protection requirements are addressed in a subsequent section.

A. TOC (51P, 51G)

Time-delayed phase and ground protection is implemented using a curve with adjustable time delay and complex

alterations, such as time adder and time multiplier. A typical calculation for a phase TOC setting is that the lowest fault current in the zone must be greater than or equal to $1.50 \cdot 51P$ (the phase TOC pickup), while maintaining at least a 12-cycle margin for coordination [4] [5].

TOC phase curves represent the baseline protection for distribution systems, and as a result are the most impacted by these schemes. As the density of reclosers increases, achieving coordination with other protection devices and peak circuit loading while still achieving proper pickup sensitivity becomes increasingly difficult. The schemes presented in this paper address these challenges by reexamining traditional coordination requirements and using innovative solutions to overcome the limitations of traditional step coordination.

B. Step Coordination

Step coordination, also known as time-delayed coordination, is a coordination method used on distribution systems where the device closest to the fault operates first, while each upstream device operates progressively slower in operation to achieve steps in coordination. Step coordination is used to improve reliability by maximizing the number of end users that remain in service after a fault interruption.

Generally, step coordination with other reclosers and peak line loading becomes impractical when the density of reclosers is greater than three. The schemes described in this paper are established industry solutions to this problem and allow for a density of more than three reclosers while still preserving traditional coordination behavior, which means that the device closest to the fault is the device that operates to lock out.

C. IOC (50P, 50G)

Phase and ground protection using an instantaneous trip is not common on distribution systems because of the difficulty of coordinating with downstream devices, particularly fuses.

When used, IOC trips tend to protect small zones with fast fault clearing, usually near the substation feeder head where the fault current is greatest in magnitude. They may also be applied to protect underground cables near the feeder head. Other times, IOC elements are necessary for coordination with transformer protection or with transmission line protection that overreaches the power transformer and into the distribution feeders.

IOC elements are problematic because they do not coordinate with downstream reclosers and must be set above the expected magnetizing inrush current to avoid nuisance trips, which can be substantial when feeders are tied together. As a result, the pickup sensitivity can be compromised, requiring additional complex solutions such as load-encroachment supervision.

FLISR and the protection schemes discussed in this paper are already complex; therefore, unnecessary IOC-related complexity should be avoided whenever possible.

D. Fuse-Saving

Fuse-saving is a protection scheme using instantaneous trips or fast TOC curves. It is designed to detect faults past a fuse and trip to clear the fault before the fuse is damaged. Fuse-saving occurs on the first trip and, in some cases, on the second

trip, after which the faster trip condition is blocked. If the fault persists, the fuse operates to clear it. Fuse-saving is based on the principle that 85 to 90 percent of faults are transient and attempts to extend the benefits of reclosing into fuse-protected segments [6]. Many utilities use fuse-saving schemes. However, fuse-saving curves are notoriously difficult to coordinate because they are essentially instantaneous. As a result, they become problematic in applications with a high density of reclosers, as they may overtrip other reclosers outside the scheme.

E. Sequence Coordination

Sequence coordination is a method for partial coordination of fuse-saving curves that prevents the upstream relay from tripping if the downstream relay clears the fault before the upstream relay trip initiation time. Some relays achieve this through built-in logic, while other relays require customized programming. Regardless of how sequence coordination is achieved, it suffers from the difficulty of coordinating instantaneous trips in systems with high recloser density and is therefore only utilized when fuse-saving is employed.

F. Fuse-Sacrificing

The opposite of a fuse-saving curve is a fuse-sacrificing curve, which occurs when the fault is beyond the fuse, allowing the fuse to operate while the upstream relay uses step coordination to avoid overtripping. Coordination is achieved by delaying the TOC so that it operates slower than the fuse-clearing curve, typically with at least 3-cycle margin [4] [5].

G. Directional Protection

Directional protection is a protection scheme in which a directional element supervises an overcurrent element to ensure that the overcurrent element operates only for faults in a specified direction [4] [5] [7]. Directional protection was not common on distribution systems until the emergence of a high penetration of DERs. Today, it is commonly used to ensure that a recloser does not trip for an upstream fault when a downstream DER is backfeeding through it, also known as sympathetic tripping [4]. Most FLISR systems rely on accurate fault location; therefore, a sympathetic trip may cause the FLISR system to identify either the wrong zone or multiple zones, resulting in incorrect isolation and service restoration.

H. Reclosing

The process of automatically closing a line following a protection trip is known as reclosing [6]. The fault may or may not still be present when the line is reclosed. This is sometimes referred to as testing the line and should not be confused with a system operator manually closing the line after a lockout to determine whether the fault is still present.

Reclosing schedules are generally not affected by protection schemes. However, it is recommended that reclose open times be increased to ensure that communications signals are properly transmitted and received, particularly where cellular radio is used as the primary communications medium.

Reclosing functionality is impacted depending on the protection scheme. CAT and FRS schemes can follow normal coordination logic when determining reclose shots and times, whereas VGR uses unique stepped reclosing logic that allows for high-density coordination.

V. APPLICATION OF ELEMENTS TO SCHEMES

This section provides a detailed analysis on the protection elements discussed previously, breaking down each element and its unique impact on the protection schemes under consideration. The intent is to provide the reader with guidance on the pros and cons of each protection element within each relay scheme to assist in deciding which protection scheme best suits their needs. There is no preferred approach; rather, readers must evaluate the pros and cons of each option and decide which approach is best suited for their project.

A. VGR

TOC protection is the basis of a VGR scheme. Each coordination group uses a common phase TOC curve and pickup setting to protect its zone. A typical calculation for a phase TOC setting for fault sensitivity is that the lowest fault current in the zone must be equal to or greater than $1.50 \cdot 51P$ (phase TOC). A typical calculation for load sensitivity is that the 51P setting must be at least 1.05 times the maximum expected line loading and must coordinate with upstream and downstream groups with at least a 12-cycle margin.

It is recommended to set the pickup setting to at least 1.05 times the largest conductor thermal rating to ensure coordination with maximum loading conditions, provided this setting maintains adequate sensitivity for end-of-zone faults. Coordinated ground elements are not recommended in this scheme because they add multiple layers of complexity by requiring coordination with upstream and downstream phase and ground curves. If downed-conductor protection is desired for public safety and is a higher priority than guaranteeing proper coordination, a slow, nonreclosing ground element with a sensitive setting may be used.

With the pickup-setting methodology established, the coordination requirements for the phase TOC elements can now be examined. Phase TOC curves are step-coordinated in a VGR scheme similarly to a traditional protection scheme, except that each coordination group uses identical settings. During the initial TOC fault detection and trip, coordination must be maintained with devices outside the VGR scheme. The most common of these devices are lateral tap fuses and noncommunicating reclosers. If a device in a coordination group were to overtrip a noncommunicating device, it would subsequently activate its fast curve and trip to lock out for a permanent fault outside the coordination group zone. In this scenario, due to the stepped reclosing and activation of the fast curve, only the edge device of the relevant group should trip to lock out. The fast curve activated during reclosing must also be coordinated with noncommunicating devices to ensure these devices are not overtripped during the reclose cycle for faults that evolve or migrate outside the initial faulted zone.

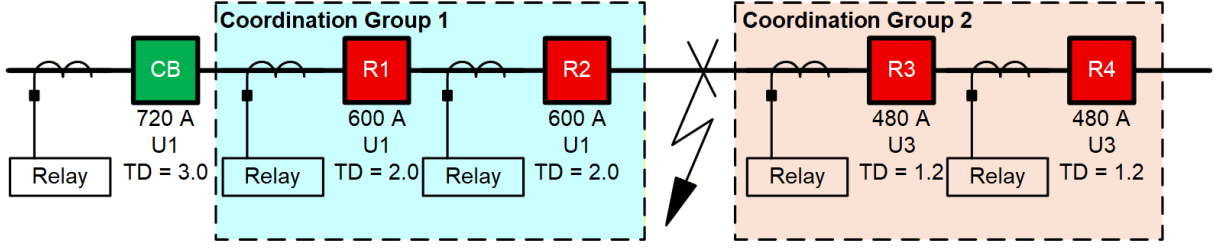


Fig. 3. Example IOC Overreach

It is not recommended to use IOC settings in a VGR scheme because reliable instantaneous coordination is often difficult to achieve. When IOC elements are used, they should be set to underreach the next downstream coordination group to maintain proper coordination. In many VGR applications, the close proximity of devices of a coordination group renders this nearly impossible. For example, in Fig. 3, if the CB had an IOC element enabled, it would trip and lock out for a fault downstream of R2, bypassing the VGR logic. Note that VGR devices do not need to be physically or electrically close to one another; their spacing depends on their circuit topology. However, discussions typically focus on devices physically and electrically close to each other because they represent the worst-case scenario.

Like IOC protection, fuse-saving is incompatible with a VGR scheme due to the inherent problem of overtripping built into fuse-saving. For utilities that currently use fuse-saving and wish to implement VGR, it is recommended to move fuse-saving to the head of the lateral tap by installing a lateral recloser coordinated with the upstream three-phase coordination group. Additional fuses can then be installed on the downstream tap and protected by the lateral recloser. Since fuse-saving is not used, sequence coordination is also not used.

As a result of eliminating fuse-saving operation and sequence coordination, VGR schemes are inherently fuse-sacrificing because they have three-phase devices. However, as stated previously, fuse-saving can still be maintained on lateral taps by installing a noncommunicating recloser at the head of the tap and implementing the fuse-saving curve in that device.

Since VGR schemes do not use fuse-saving, DER-induced sympathetic tripping of a device on its TOC curve is less likely. However, this possibility should still be checked. Where DERs can contribute sufficient fault current to cause sympathetic tripping, directional protection may be required. In such cases, the TOC curves in that coordination group must be configured as directional to prevent operation for reverse faults that occur behind the device or, where possible, set above the DER backfeed current.

Careful consideration must be given to the fast-curve settings. Per IEEE 1547 requirements [7], it is expected that all DERs be offline after the first reclose. If a DER were to island or re-energize, it is conceivable, although unlikely, that it could backfeed into the fault and activate the fast curve. In most cases, DER backfeed will not be strong enough to trip either the TOC or fast curve. Conversely, the TOC and fast-curve pickups are usually set higher than the DER backfeed. Therefore, this becomes a concern only when the TOC and fast-curve pickups

cannot be set greater than the DER backfeed without compromising sensitivity rules.

VGR schemes inherently use reclosing in the same manner as traditional protection schemes. The existing reclosing schedule can be maintained within each coordination group; however, it is recommended to delay the first reclose by at least 2 seconds to allow all DERs to trip. A delay of 5 seconds is preferred because this overrides the IEEE 1547-required tripping time of 2 seconds [7] and provides an additional 3 seconds for anti-islanding algorithms and DER interconnection protection to activate, as well as extra time for the fault to self-clear. VGR schemes also use voltage to guide the reclosing process, which adds an additional time delay into the total reclose cycle of the coordination group.

B. CAT Primary Protection

CAT schemes are communications-based and operate similarly to a directional comparison blocking scheme [8], although the requirement for high-speed tripping is less stringent. Generally, a CAT scheme is used where recloser density is extremely high, as measured by physical or electrical proximity, and where lines are short, reducing the cost of installing fiber. When a high-speed communications medium is available, high-speed tripping can be used. This can be done by either TOC or IOC protection, as dictated by the needs of the circuit.

Distribution circuits will contain fused lateral taps that require coordination. Since fuses are noncommunicating and consequently outside the CAT zone, phase TOC remains the preferred primary form of protection. Where fuses are not used, an IOC element with a time delay (definite-time element) may be used instead. It is possible to coordinate the definite-time element with the largest fuse on the circuit, thereby eliminating the need to use a TOC element entirely, assuming the required time delay provides an acceptable clearing time. However, the use of a TOC curve on long circuits to coordinate with fuse-clearing times may be required, as fault current drops off considerably at long distances.

Other than coordination with devices outside the CAT zone, step coordination is not required in a CAT scheme. Pickups must still be set greater than the maximum load current to ensure no assertions occur by load and set less than the minimum fault current within the CAT zone, as in a VGR scheme. Because CAT schemes are most commonly found on short lines, pickup is rarely a concern and can be easily standardized across all devices in a circuit.

Once appropriate pickup settings have been established, the IOC elements can perform two functions in a CAT scheme. A low-set element provides fault detection and sends the blocking signal. A definite-time IOC element used for protection. It is possible to use the same definite-time protection element for both functions by sending the block on pickup ($50P_n$) and the trip command on time-out ($50P_nT$), provided the common pickup meets the protection sensitivity requirements.

Fuse-saving is difficult to apply in a CAT scheme because the trip time of the fast curve must be slower than the communications propagation time while still being fast enough to save the fuse. For moderate- to large-size fuses subjected to high currents, the clearing time is usually no more than about 3 cycles, making saving the fuse difficult while still ensuring proper delay for the blocking signal to propagate. Small fuses often clear in subcycle times, making saving the fuse impossible. Furthermore, worst-case fuse-clearing times cannot easily be standardized unless all fuse sizes and clearing times are known, which is generally unrealistic. As a result, fuse-saving is generally not used in CAT schemes. Since fuse-saving is not used, sequence coordination is also not used.

CAT schemes are generally fuse-sacrificing by design. One advantage of using a CAT scheme is high-speed clearing. Any delay introduced to coordinate with the lateral fuse reduces the speed advantage of the high-speed clearing in a CAT scheme; therefore, the use of fuses should be carefully considered when designing the protection scheme.

For CAT schemes, directionality is not required. Edge devices located at the boundaries of the CAT zone use special settings that account for the direction of power flow. However, when DERs are large enough to cause sympathetic tripping or, in this case, assertion of the low-set fault-detection element, directional protection becomes an important consideration. If tripping devices in line with the backfeeding DER is acceptable, directional supervision is not required. However, if operation of these devices is not desired, directional supervision must be used to ensure devices trip only for faults in the desired direction, usually forward toward the fault. The current implementation of CAT schemes does not use directional indication or directional protection. If these functions are desired, the setup time and cost of implementation should be carefully considered.

Beyond fault detection and trip logic, CAT schemes must also address post-fault system restoration through reclosing. CAT schemes use reclosing like a traditional protection scheme and therefore may keep the existing reclosing schedule. Like a VGR scheme, it is recommended to delay the first reclose at least 2 seconds.

C. CAT Backup Protection

A CAT scheme should include a backup scheme for situations for when the communications medium has failed. One of the most common occurrences is a broken pole that serves the communications wire. In this case, any devices that lose communications revert to traditional TOC coordination. Therefore, TOC protection and coordination must still be considered in a CAT scheme, even though they are not the

primary form of protection. This backup scheme may be a VGR or FRS scheme, or a simple traditional overcurrent scheme. Furthermore, devices should continue to transmit blocking signals during a loss-of-communications situation in the hope that neighboring devices still receive the blocking signal and operate per the CAT logic.

Consequently, protection settings generation should follow traditional distribution protection standards for selectivity and sensitivity. These standards are not covered in this paper because they are often unique to the utility. If no such standards exist, IEEE C37.230 [4] should be referenced.

D. FRS

An FRS scheme follows the traditional rules for distribution protection, including sensitivity and selectivity. However, because the centralized FLISR system reconfigures the power system to isolate the fault and restore service to end users after a device on the faulted circuit operates to lock out, reclosers and other fault-indicating switches can be placed in close proximity without the need for coordination. This is accomplished by programming the controls to function as intelligent switches that provide fault indication. As a result, traditional step coordination can be eliminated within a large area, usually about 5 miles from the source based on the impedance of a 336 aluminum conductor steel-reinforced cable. Protection settings can therefore be largely standardized by using a phase TOC set around 1,000 A primary. This pickup will almost always exceed 1.05 times the conductor thermal rating while remaining below the minimum fault current in the protected zone, assuming a typical-sized substation transformer rating of 10 MVA or greater. The 5-mile distance is typically where fault current drops enough that a second protection device is needed. Consequently, the next in-line recloser cannot be an FRS.

Since this device has protection settings, typical coordination considerations are required. The curve shape, time dial, and any complex modifications can be standardized to coordinate with the largest lateral fuse size and the first downstream recloser(s) to protect the next zone. In this way, the FRS scheme functions and protects similarly to a VGR scheme but does not require the stepped reclosing found in the VGR scheme.

The FRS scheme follows all the rules for traditional overcurrent coordination with all upstream and downstream devices.

IOC elements are not preferred in FRS schemes for the reasons stated previously; however, this scheme offers more flexibility in application than the others discussed. Most devices on the circuit operate as FRS devices, and therefore overtrips are intentional. For example, if an IOC element is required on the feeder CB relay, any downstream reclosers overreached by that IOC element can be programmed as FRS devices. This eliminates concerns about overtripping because those devices are not intended to trip; rather, they are intended only to report a fault. IOC elements are also used by FRS devices to detect a fault and provide indication to the centralized FLISR system. This is accomplished by setting one IOC element equal to the pickup of the next upstream protection

device, with a two-cycle time delay to coordinate with magnetizing inrush currents, and a second IOC element set at twice the pickup of the first element with no intentional time delay. Other utilities have used this or a similar approach with continued success.

FRS schemes can be fuse-saving or fuse-sacrificing as desired. Because fuse-saving trips are active only on the first or second operation, overtripping and fault indication are not concerns. To limit overtrips and improve the Momentary Average Interruption Frequency Index (MAIFI), it is recommended to only implement fuse-saving on reclosers that protect radial taps.

If fuse-saving is used, sequence coordination can always be enabled. There is little downside to enabling this setting during normal system conditions, even when there are no other fast trips to coordinate with. As a result, always enabling sequence coordination allows for elimination of a human performance error associated with forgetting to activate the settings when needed.

However, some utilities have experienced overtrips during storms due to sequence coordination increasing shot counts. This happens when upstream fast curves do not overtrip but instead detect a downstream fault and increment the shot counter. A subsequent fault within the protection zone of the upstream device causes a premature lockout because the shot counter has already been advanced by the sequence coordination. One possible solution is to implement a global storm-mode, such as a supervisory control and data acquisition (SCADA) command that turns off sequence coordination or fast curves during storm events.

FRS circuits can be operated as fuse-sacrificing without any changes to protection settings or schemes. As discussed previously, fuse-saving is recommended only for radial taps. As a result, many circuits often adopt a hybrid approach in which fuses on the circuit backbone are sacrificed while fuses on radial taps are saved.

Directional protection is not normally required in an FRS scheme since the only requirement for FLISR is fault location. However, when DERs are introduced, sympathetic tripping requires that the device tripping in the incorrect direction provide a directional indication so that FLISR can correctly identify the faulted zone. With directional indication enabled, FLISR determines the fault location by accounting for the fault magnitude, faulted phase(s), and direction of fault current on devices that tripped. The directional indication is activated on any trip, not just a lockout, since the device that sympathetically trips will often do so only during the initial fault. After the first trip, the DER should remain offline.

In addition to fault-detection and fault-location considerations, the reclosing philosophy remains largely unchanged. Reclosing is used in the normal manner. As with VGR and CAT schemes, it is recommended that the first reclose be delayed by at least two seconds for the same reasons discussed previously.

VI. HARDWARE REQUIREMENTS

This section addresses the minimum equipment needed to implement each coordination scheme and provides recommendations on the optimal approach. It should be noted that even minimal implementations of a FLISR system can be expensive; therefore, careful planning, preparation, and evaluation must be done to ensure the project is successful.

It is encouraged that equipment installations be standardized, particularly for fault-reporting and tripping devices. These devices do not always have to be reclosers with programmable controls; however, it is often more cost-effective to standardize on a single build and use the programmable capabilities of the control to implement the desired functionality rather than purchase multiple equipment types to reduce material costs. For example, it is often best to standardize reclosers with the same load and fault-interrupting capabilities as the worst-case device, even if this results in overbuilding at some locations. This approach provides flexibility, accommodates future growth, and, given the typical 20-year lifespan of these devices, helps prepare the system for many unexpected future outcomes.

It is also encouraged to standardize the control platform. A programmable control allows each device to be configured with tailored functionality and enables easy reprogramming in the future if the use case for that location changes. For example, an FRS device can become a protection recloser as a result of circuit expansion. Standardization should also extend to all devices inside the control box, such as the radio, remote terminal unit (if used), dual power supply, and voltage sensing.

A. VGR

1) Recloser

All devices in the VGR scheme operate as traditional reclosers with a modified reclosing scheme. As such, each device requires a mechanical recloser that is rated to be fault-interrupting capable for the distribution system under consideration. It is recommended that all reclosers use the same interrupting rating to reduce the number of required design standards to one standard and to ensure that any recloser can interrupt a fault if it is transferred to an adjacent circuit with higher available fault current.

2) Sensing

Because VGR devices rely on traditional recloser protection functions, protection-class current sensing is required for all devices. Particular attention should be paid to the direction of the CT polarity of the reclosers being used, as CT polarity markings are not standardized. This is especially important when directional protection is implemented. However, even in a system without DER, crews may inadvertently install a recloser facing the wrong direction on the pole, resulting in incorrect CT polarity orientation. Using an identical recloser for all VGR devices simplifies CT polarity consideration by reducing them to a single standard; however, it does not account for crews hanging the device on the wrong side of the pole.

VGR requires voltage signals to supervise the reclosing sequence through a live-dead check. Therefore, the minimum requirement is single-phase sensing on the source-facing side of the device. However, if one side of the recloser lacks voltage sensing, the VGR scheme cannot operate when the feeder is energized from that side. For this reason, it is advised to use, at minimum, single-phase potential sensing on both the source- and load-facing directions. Not only does this allow the VGR scheme to operate under both normal and reverse directionality when the feeder is supplied from an alternate source. It also means that the device can be installed backwards, whether intentionally due to space constraints or unintentionally during installation. The use of low-accuracy voltage sensing is sufficient for the VGR application.

3) *Power Supply*

The VGR scheme requires devices to operate when both sides are de-energized. Additionally, the FLISR scheme may operate devices within a de-energized zone during restoration. Therefore, a backup battery is mandatory and should be monitored, as a failed battery may impact both the protection and the automation scheme.

Since FLISR may perform restoration from alternate sources and reverse power flow for extended durations following protection events, it may be beneficial to have power potential transformers (PTs) installed on both sides of the switching device.

4) *Recloser Control*

The voltage-guided modification to the traditional reclosing scheme is commonly configured through custom logic within the recloser control. Therefore, the recloser control must support custom logic to implement the voltage-guided behavior to supervise or stall reclosing. Most modern microprocessor-based recloser controls support this capability.

5) *Communication*

VGR does not require communications to operate and can therefore perform the primary protection functionality without any external communications. If these devices are to be controlled as part of a FLISR system or monitored through a SCADA system, low-speed communications are sufficient. Common applications may use cellular Ethernet (3G or 4G LTE) or Ethernet radios. Relative to an FRS scheme, which requires a centralized FLISR system or advanced distribution management system (ADMS) to achieve full functionality, VGR can perform proper isolation on its own, which may make it more sustainable at a lower cost.

B. *CAT*

1) *Recloser*

All devices in a CAT scheme operate as traditional reclosers with a modified protection scheme. As such, all devices require a mechanical recloser with protection-class current sensing that is rated as fault-interrupting capable for the distribution system that is being considered. It is recommended that all reclosers use the same interrupting rating by reducing them to a single design standard and ensuring that any given recloser can

interrupt a fault if transferred to an adjacent circuit with a higher available fault current.

2) *Sensing*

CAT schemes do not use voltage as part of the protection scheme. Therefore, requirements for potential sources are based on use cases for the device and any requirements of the backup coordination scheme. For example, if there is the possibility of closed-transfer operations by remote operators or line crews, it is common practice to have at least a single-phase potential sensing on the normal source side and a single-phase synchronization PT on the normal load side.

With the rapid growth of DERs across power systems worldwide, it is recommended to use at least three voltage-sensing devices on the source side so that directional protection can be added as needed. Additionally, DER protection schemes may include synchronism-check functionality or live-line and dead-bus checks, in which case it is preferable to have voltage sensing on all six bushings to ensure no phase is energized prior to closing. Current sensing has identical concerns to those discussed for the VGR scheme.

3) *Power Supply*

The CAT scheme requires the communications network to always remain online to keep the primary protection scheme armed. Therefore, a backup battery is mandatory and should be monitored since a failed battery will degrade system performance.

Because FLISR may perform restoration from alternate sources and reverse power flow for extended durations following protection events. The recloser should be equipped with power PTs installed on both sides of it.

4) *Recloser Control*

The CAT requires support for the chosen high-speed communications protocol, as well as the ability to implement the relevant blocking logic. This functionality may be available within a modern microprocessor recloser control, or it may necessitate an additional logic processor or communications module.

5) *Communication*

CAT requires communications at protection-level speeds, although the strict definition of this varies. The original design of this protection scheme allowed a communications delay of up to 3 cycles (50 ms) to maintain coordination with fuses [2]. However, other user applications may have more or less stringent requirements. In general, the communications infrastructure must be capable of consistently providing communications delays to meet the specific application with high reliability.

If the objective is sub-100 ms, this was traditionally feasible only with physically connected networks, such as copper or fiber Ethernet. However, deploying a fiber network across the distribution system is a significant expenditure when such infrastructure does not already exist or cannot be leveraged for other purposes.

Recently, several studies have been conducted regarding the feasibility of using the IEC 61850 Generic Object-Oriented

Substation Event (GOOSE) protocol over cellular networks with varying success. Direct transfer trip schemes using 3G or 4G LTE networks have reported operating times between 100 and 200 ms [9]. Proof-of-concept studies using simulated 5G networks have shown network delays of 10 ms, which may be viable for these applications. However, such systems have not yet been deployed or proven using real networks [10]. As these new technologies are tested in real-world scenarios, they may show that CAT network infrastructure is less prohibitive than it was when the scheme was first designed. However, this paper does not make any claims regarding the feasibility at this time.

C. FRS

Unlike CAT and VGR schemes, the FRS scheme combines both traditional protection devices (reclosers) and FRS devices (switches). The hardware requirements for the traditional protection devices within the FRS scheme have no additional requirements based on the FRS scheme; therefore, the effective requirements for these devices are less stringent than those described previously under VGR, as they do not require user-configurable logic.

The FRS devices have minimal requirements. As such, there are two common approaches: either a minimal hardware configuration is used to reduce costs, or a standard recloser installation is used for consistency across field hardware. Experience has shown that using a minimal hardware configuration to save money results in short-term benefits but increases costs in the long term, as circuit configurations change over time. It is recommended to always use reclosers with programmable controls for this reason. The following subsections describe the minimum viable hardware approach for FRS devices. If a standardized approach is used, refer to the requirements described in Section VI.A.

1) Switch

A mechanical switching device is not required to be fault- or load-interrupting capable for this application. If the control systems are aware of the limitations of the switching device, a switching device without load- or fault-interrupting capability is a viable option for this application. If the switching device is load- or fault-interrupting capable, these capabilities may provide additional benefits to external control systems; however, they are not strictly required.

It is recommended that all FRS devices use the same reclosers and controls as the protection devices for the previously stated reasons.

2) Sensing

FRS devices require a means of detecting fault current, but protection-level accuracy is not required because the devices do not need to coordinate with one another. This provides FRS devices with a wide range of options. Traditional current sensors may be used, allowing flexibility if set points need to be changed for contingency configurations. Alternatively, dedicated wireless fault sensors may provide sufficient accuracy for the application while reducing hardware and installation costs, although they are less configurable.

FRS devices do not require voltage sensing for the primary overcurrent fault operating mode. However, if FRS devices are

used for series fault detection (open-phase detection) by FLISR, three-phase voltage sensing on the source side is required. If voltage sensing is unavailable, series fault operations are limited to the nearest device with voltage-sensing capability. As such, a common approach is to have low-accuracy, three-phase sensing on the source-facing side of FRS devices.

It is recommended that voltage sensing be used on all six bushings to account for DER growth for the same reasons as the CAT scheme. This is another benefit of making the FRS devices identical to the protection devices, as all sensing devices have full voltage-sensing capability. FRS schemes have the same current sensing concerns as VGR and CAT schemes.

3) Power Supply

Since FRS devices may not be load-interrupting capable, they will primarily be operated by FLISR while de-energized. As such, a backup battery is mandatory. A backup battery for the traditional protection devices in the scheme is also recommended and should be monitored. If the battery fails during an event, this may limit the effectiveness of FLISR operations, but it will not directly harm the primary protection scheme.

As such, a single power PT on the normal source side of the switching device may be sufficient for a simple FRS device. It is recommended to always have voltage sensing on both sides of the device for the standardization reasons mentioned previously in this section.

4) Switch Control

The FRS device is intended to operate as a remotely controlled switch. As mentioned in earlier sections, the fault-detection capability of the device is minimal. As such, a low-cost switch controller may be sufficient for this application.

If independent fault sensors are used as described in earlier sections, a common communications module may be beneficial for combining switch-control functionality and fault-sensing capability into a single communications channel. If the FRS device uses an intelligent control, it follows the same rules as the protection control and therefore has the same hardware requirements.

5) Communications

FRS requires communications to provide value. For these devices to be controlled as part of a FLISR system or monitored as part of a SCADA system, low-speed communications are sufficient. Common applications may make use of cellular Ethernet (3G or 4G LTE) or Ethernet radios. Some FLISR systems rely on time-stamped signals to determine fault location. When cellular devices are used, typical propagation delays may range from 0.5 to 1.5 seconds. Therefore, it may be recommended to increase the first reclose time to at least 2 seconds to assist with data collection.

VII. SCALABILITY CONSIDERATIONS

Scalability for protection schemes have various components. Electrically, maximum allowable fault-clearing times or circuit loading may limit to the maximum number of protection devices in a series. Administratively, differences between devices or device settings can make systems difficult to

maintain. Scheme design considerations may also limit future expansion and improvements within an existing area without significant changes. Additionally, converting existing hardware to new schemes drastically reduces the cost, whereas mass hardware replacement can drastically increase the cost.

For each of these schemes, only the variations between them are addressed. Scalability considerations common to all schemes include commissioning effort, SCADA communications and controls testing, FLISR communications and controls testing, pole space planning, and diminishing returns as device counts increase.

A. VGR

1) *Fault Detection and Lockout Time*

For a sequence of VGR devices in a series, fault detection and clearing times are similar to traditional coordination because each coordination group of VGR devices uses the TOC set points of an individual traditionally coordinated device. As a result, scalability is equal to that of a traditional overcurrent protection scheme that is step-coordinated, except that the scalability of each coordination group is limited only by pole space. In other words, there are likely to be only two or three recloser groups that can be coordinated per circuit, but the number of reclosers within each coordination group is mostly unlimited.

With VGR, the time to lock out will vary based on the number of devices within the group that are upstream of the fault and will participate in the stepped reclosing sequence. If the fault is downstream of the first device, a traditional reclosing sequence will occur. For each additional device, the reclosing sequence will have an additional delay based on the delayed stepped reclosing of each device.

As such, the best-case lockout time matches traditional coordination, while the worst-case lockout time increases linearly with the number of devices in a coordination group. Generally, the increased lockout time is not an operational concern and is therefore not a scalability issue. However, the worst-case sequence to lock out should be considered when determining whether a configuration with many reclosers in a coordination group provides an acceptable service-restoration time for FLISR.

2) *Settings and Coordination Complexity*

The VGR logic scheme for reclosing is more complicated than traditional reclosing; however, once developed, it is plug-and-play across all devices. As such, initial deployment of a VGR scheme will require greater effort to integrate into an existing distribution system. Most likely, each existing control will need to have a new logic file loaded with the new VGR logic implemented.

The relay logic for all reclosers in a VGR system is identical. Protection settings for devices in a VGR system are identical for all devices within a coordination group. This combination results in the number of unique protection settings being equal to the number of coordination groups. Due to the grouping behavior, more devices may be added easily to existing systems because the new devices will have settings matching the existing logic and curves of their coordination group.

If the scheme is to be preserved under contingency scenarios in which a feeder may be supplied from alternate sources, such as after FLISR restoration following a permanent fault, the assignment of devices to coordination groups may be maintained; however, alternate protection set points will be required. This will allow the limited number of settings to be maintained while supporting contingency. Alternatively, the same set points may be reused in contingency scenarios, recognizing that initial coordination may be incorrect. In such cases, multiple coordination groups within the VGR scheme may trip initially; however, the VGR sequence will still re-energize the system up to the proper isolation point.

3) *Expandability Postdeployment*

Once a VGR scheme is in place, additional devices may be added within an existing coordination group with minimal impact. As long as the total time-delay of the series reclosing sequence is within allowable limits, additional devices require no additional coordination studies or modifications to existing relays. In this scenario, no existing devices require settings changes or recommissioning since there is no cross-device interaction.

If an additional coordination group is required to support additional devices, the considerations described previously need to be considered for the new group. For these reasons, VGR schemes scale well postdeployment, provided that the new devices are carefully planned.

4) *Reusing Existing Hardware*

Existing reclosers may be converted into devices within a VGR scheme through a logic settings change, provided they have the required voltage-sensing and logic capabilities. If existing devices were installed based on the limits of traditional coordination, one possible conversion strategy is to use those devices as the basis for each VGR group. In this way, all relevant templates are created with the initial conversion, and new devices can be added easily.

Since communications are not required for the VGR scheme reusing existing recloser and control hardware becomes straightforward, provided the controls have the capability to accept the new VGR logic.

5) *Additional Considerations*

Existing commissioning test scripts or procedures may be adapted to test the VGR scheme through the inclusion of test states that simulate the stepped reclosing of upstream devices. It is recommended to test logic functionality in a laboratory environment, with only functional tests performed onsite, since the logic will always be identical. As a result, the scalability of commission testing is simple.

B. CAT

1) *Fault Detection and Lockout Time*

One of the defining aspects of a CAT scheme is that the fault-detection time and lockout time are independent of system size. Regardless of how many total devices are in a series or the fault location, the CAT scheme results in a consistent operating speed and reclosing sequence. Scalability is therefore limited

only by availability of pole space or the underlying communications network bandwidth.

2) *Settings and Coordination Complexity*

The CAT logic scheme is the most complicated out of the three schemes discussed for initial development. However, it has the least variety once implemented.

Relay logic and protection settings for all reclosers in a CAT system are identical. Therefore, the only logic or protection difference between devices are changes to support the contingency protection scheme. If the contingency protection scheme implements either VGR or FRS behaviors, the scalability of relay settings will match. Similarly, the requirements for coordination studies will primarily depend upon the contingency implementation.

Unlike VGR or FRS schemes, CAT schemes have a high-speed communications settings component. CAT devices are required to communicate with their electrical neighbors, which results in every device having a unique set of devices that it must report and listen to. If IEC 61850 GOOSE is used for this functionality, as is done in [2], this necessitates the administration of a unified Substation Configuration Description (SCD) file. Typically, all devices that may need to communicate will be housed within a single SCD file, resulting in one file per electrically independent network.

The CAT scheme is preserved under contingency scenarios when the feeder may have its directionality changed or be supplied from alternate sources. As long as the neighboring devices are identical, the scheme will provide protection coordination regardless of the exact fault current path. However, if a backup coordination scheme exists for times of communications loss, the backup settings may introduce additional variety to support these contingency scenarios.

3) *Expandability Postdeployment*

Within the relay logic and protection settings, the only changes to support adding new devices to an existing network would be those to support contingency scenarios and the relevant contingency protection scheme. Depending on the contingency scheme, this may or may not require changes to the logic or protection settings of in-service devices.

The addition of new devices within an existing system will change the defined neighbors for in-service devices. This necessitates changes to the communications settings of existing devices to account for the change in neighbors. Depending on available diagnostic tools, deploying these changes may be less intensive than changes to relay logic or protection settings.

Depending on the high-speed communication media and protocol used, additional devices may require modifications to the existing communications network. This may take the form of splicing existing fiber-optic cables to add new network switches at new device locations, modifying existing routing or network-management strategies, or updating existing switch configurations.

These factors make postdeployment scalability more difficult than in other schemes since a device cannot be added to a network without touching its neighbors. Therefore, it is recommended to consider a reasonable time frame of future

deployment during the initial project plan and build out accordingly to alleviate some of the complexity of future expansion.

4) *Reusing Existing Hardware*

Out of the three schemes considered, a CAT scheme is likely to require the most modifications to adapt existing hardware. Unless high-speed protection schemes are already in use, both the communications hardware and the relay capability for high-speed communications protocols may be lacking. Similarly, additional hardware may be necessary to implement the logic required by this scheme. For these reasons, existing hardware may need to be upgraded to implement the scheme. Even if the recloser and control can be adapted to the new hardware, it may be more cost-effective to replace the entire control with a new one that has all the components preinstalled. There is no clear path for reusing existing hardware, so labor and material cost must be carefully considered when planning the project.

5) *Additional Considerations*

Since the communications network becomes a critical part of the protection system, device testing must also account for the communications component. Other literature describes the idea of implementing a communications-testing feature into the core CAT settings, which may simplify system testing by allowing a dedicated test mode in the recloser control that verifies communications network latency is within acceptable behaviors [2]. If such a system is implemented, standard commissioning procedures may be used if the device under test is placed into the appropriate mode.

As with the VGR scheme, it is recommended to perform extensive laboratory tests to ensure correctness of logic, with only the necessary functional and communications testing performed during commissioning. This approach simplifies scalability as additional devices are deployed.

C. *FRS*

1) *Fault Detection and Lockout Time*

For an FRS scheme, the operating time and lockout time are dependent upon the traditional protection devices and protection scheme located between switches. Because of this, the quantity of traditional protection devices is dependent upon traditional protection considerations.

The presence of FRS devices has no impact on initial fault-clearing or lockout times, since the FRS devices may not be fault-interrupting capable and do not participate in the reclosing scheme. However, FRS devices provide benefit only if the external control system, whether a FLISR system or a SCADA operator, can accurately determine which FRS devices are appropriate to operate.

If operations are based purely on the fault reporting of FRS devices, an effectively unlimited number of FRS devices may be installed between traditional protection devices. Alternatively, if operations are instead driven by an impedance model fault-location calculation, the number of devices may be limited based on the model precision. Scalability is therefore straightforward because a nearly unlimited number of FRS

devices can be added between protection devices, limited only by pole space.

Fault location in an FRS scheme is most effective when fault magnitude and phase information is sent to FLISR. This allows FLISR to determine the near-exact location of the fault by performing a short-circuit study on the line, plotting the location of the fault, and opening the upstream and downstream devices. A binary lockout point is also sent to FLISR to assist in quickly identifying the zone of the fault. FRS devices with intelligent controls will send identical fault magnitudes and phases as the protection device, whereas FRS devices with simple controls may send a binary fault flag, indicating a fault is downstream of the FRS device.

In either case, FLISR will be able to identify the zone. The difference is that fault phase and magnitude provide an accurate location within the isolated zone. If the length of the line between the zones is large or access is limited, such as in mountainous or rural areas, this additional accuracy can provide significant System Average Interruption Duration Index (SAIDI) improvements by reducing the patrol time required to locate the fault. Regardless of which fault-locating method is used, scalability is still limited only by available pole space.

2) *Settings and Coordination Complexity*

An FRS scheme consists of traditional protection CBs and reclosers alongside FRS. As such, the settings will consist of relay logic and protection settings for traditional reclosers and breakers alongside settings for FRS.

Since FRS devices do not actively participate in tripping or reclosing, there is no requirement to maintain coordination with traditional protection devices. A common approach is to set the FRS device overcurrent elements high enough to avoid operation under load conditions (typically set to at least two times the load), but low enough to ensure that they assert for a fault. If the highest feeder load and the lowest fault current availability on a feeder have enough separation such that these requirements do not overlap, a single set of set points could be applied to all FRS devices on the feeder. Another common option is to set the FRS device equal to its nearest upstream protection device.

If the scheme is to be preserved under contingency scenarios where a feeder may be supplied from alternate sources due to a permanent fault and FLISR restoration, the traditional coordination devices likely need alternate protection set points configured for these scenarios. Additionally, the simplified set points of FRS devices may require reevaluation; however, FRS device set points allow more flexibility than traditional coordination schemes. As a result, these devices may be able to maintain identical set points across normal and contingency configurations. This approach can simplify future expansion by allowing a common FRS pickup setting to be applied under both normal and alternate-feed configurations.

3) *Expandability Postdeployment*

Once an FRS scheme is in place, additional FRS devices may be added within existing traditional protection zones with minimal impact. Additional FRS devices have no impact on

initial fault-clearing or lockout times; therefore, there are no checks required before adding new devices.

Adding additional traditional protection devices within an existing FRS scheme requires the same considerations as adding a protection device in a purely traditional distribution network.

4) *Reusing Existing Hardware*

Since an FRS scheme consists of both FRS devices and traditionally coordinated devices, the ideal scenario is to use existing hardware as the traditionally coordinated devices. This way, any feeder can be converted to work in an FRS scheme through the introduction of FRS devices between existing hardware, assuming the existing controls meet any requirements for operating with the external FLISR system.

Alternatively, reclosers can be used as FRS devices, even though only a switch is required. As such, existing hardware may be repurposed as FRS devices if new hardware is added to serve as the traditionally coordinated devices.

It is recommended that all FRS devices be identical to the protection devices so that the FRS can function as a protection device as needed for contingency scenarios and can be converted to a protection device after deployment as needed. By making all FRS devices identical to the protection devices, postdeployment scalability is again limited only by pole space.

5) *Additional Considerations*

Since FRS devices may not fully be protection devices, they typically require a less extensive deployment process than a full-featured, traditional protection device. However, they also require a different testing script since they do not operate in the same way as traditionally coordinated devices.

If the same physical hardware template is used for both FRS devices and their traditionally coordinated devices, a clear indication should be available to identify the operating behavior of a specific device to prevent confusion. This is usually done by using a different geographic information system symbol and an indicator on the relay rotating display that states the operating mode (protection or FRS).

VIII. SAFETY AND TRAINING CONSIDERATIONS

This section examines the common safety impacts and the importance of training for implementing a distribution scheme with FLISR. These concerns are called out in this section because of the importance of considering the operating impacts of FLISR to all aspects of the distribution system, even those outside the normal realm of protection settings, such as the impact on system operators and line workers.

A. *Safety*

Safety of workers and the public is always a primary concern. Regardless of whether protection settings, communications architecture, physical equipment, design standards, or operating procedures are being engineered, safety should precedence over all other considerations. The most common safety factors related to distribution protection schemes are discussed in this section. This list is not exhaustive and should be considered a starting point. Each utility has

unique circumstances that must be considered for each unique scheme implementation.

1) *Universal Considerations*

HLT is a common industry term for close blocking on distribution systems. The primary intention of this behavior is to ensure that if a fault occurs within a work zone, the zone is isolated and is not re-energized by reclosing. This blocking may (but does not always) activate an instantaneous or fast curve to reduce arc-flash incident energy. Utilities have unique procedural names for their tagging procedures, so HLT is known by many distinct designations, such as maintenance mode, green tag, or arc-flash protection. Regardless of the name, HLT is commonly applied on fault-interrupting distribution devices, including reclosers and CBs.

At times, it may be necessary to disable or limit FLISR systems to ensure the safety of crews performing work or to address unplanned system conditions. Whereas HLT can prevent a zone from being re-energized through the protection sequence, disabling FLISR prevents zones from being re-energized by automation. This is particularly important when HLT is enabled because HLT may result in protection devices intentionally overtripping, a condition that some FLISR systems may attempt to correct. FLISR systems can typically be disabled through operator controls or status indications received from reclosers and switches. This provides several options for how to disarm FLISR systems when necessary.

With both traditional and nontraditional protection schemes, the relationship between HLT and FLISR should be considered. A common implementation is to disable the FLISR scheme on a feeder whenever HLT is activated, ensuring that restoration cannot occur within the tagged zone. Some FLISR systems may offer alternative options, such as strict adherence to work zones so that the tagged zone will not be re-energized while permitting restoration in other portions of the feeder. It is recommended that a single standard behavior be used throughout the system, regardless of the distribution protection scheme applied in any specific area. This helps all engineers, operators, and crews understand what to expect and how to perform their work safely.

Another situation where FLISR may need to be disabled is for the operation of special protection schemes (SPSs). Examples include downed-conductor detection algorithms and fire-protection schemes [11] [12] [13]. In each, these algorithms detect circuit conditions that require quick isolation and no automatic restoration, ensuring that the affected zone stays de-energized. When combining an SPS with FLISR, it is recommended to carefully consider the intent of the SPS and the desired operational outcome.

Having multiple options for disarming FLISR is beneficial because it provides redundancy; however, it is also a risk, as all options could be overlooked if multiple parties assume that someone or something else is responsible for disarming the system. The interaction of FLISR automatically disabling through status indications from devices in the field versus explicit controls from operators should be considered in how they fit into existing standard operating procedures and whether these procedures should be revised. Some utilities may prefer

multiple interlocking blocks whereas others may trust a single HLT if that is already a critical step in their procedures. There is no universal right answer, but a utility's standard operating procedures should define what is right for their operators and crews.

2) *Live-Line Work With VGR*

The VGR scheme does not use point-to-point communications; therefore, there are no equipment signal blocks or disables to be aware of when performing live-line work within the scheme. However, crews must be aware of what devices belong to the same coordination group, as all devices within a group trip and reclose together.

For example, if crews are working downstream of the last device in a group of four and a work-zone fault occurs, the fourth device would trip and remain open if reclosing is blocked on that device. The other devices in the coordination group may still perform their configured reclosing sequences unless additional controls are applied. Depending on the operating practices of the utility, the work location, and the desired isolation approach, additional reclose blocking or FLISR inhibition on the other devices in the coordination group should be evaluated to further limit automatic operations near the work zone.

3) *Live-Line Work With CAT*

A CAT scheme uses point-to-point high-speed communications to transmit the blocking signals between any neighboring devices. Therefore, careful consideration should be given to the required blocking when performing live-line work. Under normal circumstances, the high-speed network allows for fast fault clearing and prevents adjacent devices from tripping for the same fault. Therefore, if the device upstream of a fault zone has reclosing disabled, the zone will initially trip and will not be re-energized when operating nominally.

Despite this capability, the use of traditional HLT set-point modification along with reclosing disablement should be considered. Although these measures may be unnecessary under normal conditions, a loss of communications may cause one or more devices to revert to backup protection schemes, where the set-point modification helps ensure that reclosing is functionally disabled for downstream faults. Additionally, this approach promotes standardization of operating procedures between CAT-protected areas and areas with traditional schemes.

4) *Live-Line Work With FRS*

If HLT is not implemented in the FRS devices, it is sufficient to apply HLT or reclose block the upstream protection device nearest to the crew. In this scenario, the FRS devices are considered switches and are not included in the HLT tagging procedures, making tagging for live-line work straightforward.

If the FRS devices have the necessary hardware and protection capabilities, HLT may be implemented in the FRS devices. In this case, standard operating procedures should identify where and how tagging is performed. Ideally, the nearest FRS device should have HLT activated because this ensures that any fault caused by the crew is cleared by the nearest capable device, resulting in a smaller end user outage.

However, this also means that any FRS devices with HLT enabled function as protection devices and must follow the stringent requirements of protection sensitivity and maintenance. Additionally, utility operating procedures should define tagging practices for FRS schemes because FRS devices are hybrid devices, operating as switches during normal fault conditions while also serving as protection devices when line work is performed.

B. Training

Training all affected teams is an important part of FLISR implementation. Generally, the teams that need to be trained include engineers who will build the scheme, line workers who will construct the scheme, line workers who will operate the scheme locally or perform work within the zones protected by the scheme, and system operators who will oversee and operate the system and coordinate with the line workers.

It must be understood that not all affected parties will have the same knowledge of the schemes, particularly if FLISR is in use. As a result, training must be thorough, detailed, and methodical. Each affected group will require different presentations of the same material based on skill level and engineering knowledge. The remainder of this section outlines a few common strategies for these teams.

Protection engineers must understand all aspects of the FLISR scheme, including aspects they may not have traditionally been involved with, such as SCADA communications points, pushbutton operation, front-panel LED operation, and line worker procedures. Engineering training must be thorough, starting with the budget and reliability goals that drive the project, progressing through the engineering details, and concluding with operational concerns. Comprehensive documentation must be developed and maintained to ensure this knowledge is retained as resources cycle through the protection team.

Line workers must be addressed with confidence and respect. It is important to view the task from their point of view. Line work is among the most dangerous positions, and while many line workers do not have formal engineering backgrounds, they must still understand the operation of the power system at both an intuitive and technical level. Developing this expertise takes years of training and observation. Introducing a new and complex FLISR system, much of which operates outside the control and visibility of the line worker, can naturally create hesitation. Line workers must be trained by someone well-versed in all aspects of the protection and FLISR scheme who can communicate effectively in terms that resonate with line workers, with a focus on the equipment and operating procedures. The objectives of FLISR schemes are the same as traditional coordination, but they include additional automated steps. Similarly, the procedures that crews use to operate within and around these schemes are similar to those used when working with remote operators. Tagging, testing, and grounding procedures create safe environments for them to carry out their work.

System operators support safe and reliable operation under a wide range of conditions and may bring varied professional

backgrounds and experience levels to the role. Therefore, operating practices often rely on set procedures to promote consistency and safety. Training system operators should combine procedural training with technical context to explain the intent of the protection and FLISR schemes. This combination helps operators apply procedures effectively while also supporting informed decision-making when the system does not respond as expected.

IX. END USER AND RELIABILITY METRIC IMPACTS

A. Metrics Considered

While the primary focus of this paper is the viability and scalability of the protection schemes, there needs to be a way to measure the effectiveness of each scheme and their effects on end user reliability. The primary driver for increased device density is always improvement of end user experience by increasing continuity of service and reducing momentary outages (blinking lights). Utilities quantify these reliability improvements using the indices defined in IEEE 1366 [3]. While there are many different metrics, this paper only covers the most relevant to utility performance.

1) System Average Interruption Frequency Index (SAIFI)

SAIFI is the measure of total sustained system interruptions divided by total end users. This equation represents the average number of interruptions any given end user will experience annually. In this context, a sustained outage is defined as being 5 minutes or more based on the IEEE definition of sustained outage [3]. By inference, this means any trip, reclose, or restoration in less than 5 minutes counts as a momentary interruption and not a sustained interruption, thus increasing MAIFI and conversely reducing SAIFI. SAIFI is shown in (1).

$$SAIFI = \frac{\sum \text{Total number of end users interruptions}}{\text{Total number of end users served}} \quad (1)$$

2) Customer Average Interruption Duration Index (CAIDI)

CAIDI measures the duration of the sustained interruptions experienced by end users in the outage zone. Similar to SAIFI, CAIDI measures outage time; however, it is specific to the end users out of power, whereas SAIFI is a system-wide average. Utilities typically use CAIDI scores to evaluate system operator and line worker performance because they are the teams directly responsible for fixing the fault and restoring power to customers after automatic isolation and restoration. CAIDI is shown in (2).

$$CAIDI = \frac{\sum \text{End user minutes of interruption}}{\text{Total number of end users interrupted}} \quad (2)$$

3) SAIDI

SAIDI measures the total duration of sustained interruptions experienced by the average end user served by the utility over a specified period of time. Unlike CAIDI, which considers only end users affected by the outage, SAIDI provides a system-wide view of reliability by averaging the total end user outage minutes across all customers served. As a result, SAIDI reflects both the frequency and duration of outages and is commonly

used as a primary indicator of overall distribution system reliability. SAIDI is shown in (3).

$$\text{SAIDI} = \frac{\sum (\text{Duration} \cdot \text{no. of end users interrupted})}{\text{Total number of end users served}} \quad (3)$$

4) MAIFI

Finally, MAIFI measures momentary interruptions, which are different from sustained interruptions. Momentary interruptions are less than 5 minutes based on the IEEE definition of a sustained outage [3]. MAIFI, therefore, represents the average number of blinking lights phenomena that the average end user will experience. MAIFI is shown in (4).

$$\text{MAIFI} = \frac{\sum \text{Total no. of end user momentary interruptions}}{\text{Total number of end users served}} \quad (4)$$

Although FLISR systems are not required for these protection schemes, their addition affects the indices described previously by adding the additional restoration function. FLISR therefore reduces the number of sustained outages by turning them into momentary outages via the restoration of some end users after the faulted zone is isolated.

In general, FLISR will shift what would have been a sustained outage to only a momentary outage. This will, in turn, increase MAIFI, but it will directly decrease SAIFI. For many utilities, this tradeoff is favorable considering they are largely graded on SAIFI.

B. Fault Indication

The quantity of data points used to identify the faulted zone has a direct impact on CAIDI. More accurate fault locating leads to faster restoration times, thereby reducing the duration of the outage. When a utility implements these relay and protection schemes, it is common to identify the faulted zone via binary analysis. If a device detects a fault (binary '1'), regardless of whether it trips, the fault is assumed to be downstream of that device. Conversely, if a device does not report a fault (binary '0'), the fault is assumed to be upstream. Identifying the correct faulted zone is then a simple matter of finding the last downstream device that asserted a '1,' with the next device reporting a '0,' and isolating that zone. This process provides equal SAIFI reduction across all three relay schemes (VGR, CAT, and FRS).

The addition of FLISR to these relay schemes provides further SAIFI improvement by restoring service to more end users in the isolated zone. SAIDI improvements are generally proportional to the SAIFI improvements.

However, CAIDI is relatively unaffected by the specific protection scheme or by the presence of FLISR. Generally, a patrol must take place within the identified faulted zone regardless of which scheme is used. As a result, increasing the quantities of devices reduces the area of the zone to investigate, but improvements to CAIDI are limited.

CAIDI can be improved by adding additional intelligence to the fault indications of each device. These additional data points are sent to the SCADA system, enabling the operator, or an automated dispatch system, to direct crews quickly to the faulted area within the isolated zone. The additional

intelligence consists of the faulted phase(s) and magnitude(s). Identifying the phase(s) involved determines the fault type, which, when combined with magnitude, allows for the plotting of a location against the line impedance, giving an exact distance from the source.

Because distribution circuits conductors are typically nonhomogeneous, the built-in distance calculation of the relay can be inaccurate. In these cases, calculating the fault location via a short-circuit model yields excellent results, narrowing the faulted zone to a 1,500-foot bandwidth (750-foot radius). This area generally is about only five to ten spans of wire in each direction, quite a small area to patrol. Furthermore, if the fault evolves over the tripping sequence, for example, from a phase-to-ground fault to a phase-to-phase-to-ground fault, operators will often have a good estimation of the extent of the damage.

In all cases, this narrow fault-location bandwidth improves the speed of restoration; however, it offers significant improvements on long or rural circuits. In those cases, crews are often stationed one or more hours drive away from the fault location, and the identified fault location may not have accessible roads unlike in urban areas. As a result, the narrow bandwidth not only reduces patrol time but it also allows crews to plot the most direct route as possible to the patrol zone, reducing the possibility of driving long, roundabout distances that extend the outage duration.

For this reason, it is recommended that any implemented scheme should include both a binary identification of the zone and the faulted phases(s) and magnitudes(s) sent to the SCADA system.

C. Impact of VGR

Under normal conditions, if deployed without FLISR, a VGR scheme allows upstream reclosers to reclose only after verifying acceptable voltage conditions on the upstream system, indicating that the fault is not located upstream. Once the faulted section has been successfully isolated, service is restored to unfaulted portions of the feeder by maintaining isolation of the damaged segment and restoring customers downstream from the isolated zone via field ties to the same or adjacent distribution circuits. The increased sectionalizing capability results in fewer end users experiencing sustained interruptions, resulting in improvements in both SAIFI and SAIDI. End users upstream of the fault may still experience momentary interruptions associated with the recloser trip-and-reclose sequence, resulting in an increase in MAIFI, depending on how the utility counts multiple momentary outages over a short duration. In addition, local identification of the faulted zone may also improve CAIDI by quickly directing crews to the fault location.

Although these benefits are substantial under normal operating conditions, the reliability performance of the scheme can change significantly when a device failure occurs. Consider a contingency in which a downstream recloser within a coordination group fails to operate due to a mechanical failure. In this case, fault clearing now falls to an upstream device. This leads to more end users without service, increasing SAIFI due to the larger end user interruption count. SAIDI and CAIDI may

worsen as well because restoration cannot proceed until the failed device or faulted section has been identified and isolated. Since the incorrect recloser locked out due to a failure, identifying the fault zone becomes more difficult and may require more patrol time. Furthermore, multiple reclosing attempts may occur before backup protection clears the fault, potentially increasing MAIFI for customers located outside the faulted section.

However, when VGR is combined with a FLISR system, it is expected to see additional improvements in SAIFI and SAIDI when compared to VGR alone. As described previously, a FLISR system increases MAIFI as a tradeoff for turning sustained outages into momentary ones, thereby reducing SAIFI. This is because VGR improves fault sectionalization by allowing the reclosers closest to the fault to identify and isolate the faulted segment, while FLISR automates the restoration of unfaulted portions of the feeder through alternate switching paths. As a result, fewer end users experience sustained interruptions. This combination generally produces greater improvements in SAIFI than FLISR alone because the outage is confined to a smaller portion of the feeder before restoration actions begin. Additionally, automatic restoration reduces outage duration for unaffected customers, resulting in lower SAIDI.

However, CAIDI may also improve compared to a VGR-only implementation because FLISR restores service to most end users automatically, leaving only the faulted section requiring repair, ostensibly making fault locating easier, reducing patrol time.

D. Impact of CAT

Under normal conditions, if deployed without FLISR, a CAT scheme uses high-speed communications between reclosers to identify and isolate only the faulted section of the feeder. Unlike VGR, only the device closest to the fault is tripped, minimizing the number of end users experiencing both momentary and sustained interruptions and resulting in improvements to SAIFI, SAIDI, and MAIFI because fault-clearing operations are always immediately adjacent to the faulted zone. The rapid identification and isolation of the faulted section can also reduce restoration times by quickly directing crews to the faulted zone, leading to lower CAIDI.

Consider a contingency for a CAT scheme where the communications channel becomes unavailable, the scheme reverts to conventional overcurrent-based coordination. In this degraded operating mode, fault isolation is no longer based on communications-assisted selectivity, instead requiring protection devices to rely on time-current coordination to clear the fault. As a result, upstream devices may overtrip and increase the size of the outage area if not properly coordinated. Given that the physical distance between devices in these schemes are commonly very small, achieving zone coordination will be difficult and, in some cases, impossible.

The additional end users affected by this overtripping negatively impact SAIFI by increasing the number of end users out of service. SAIDI is also adversely affected because faulted zones are more difficult to identify in larger areas. Since SAIDI

is increased, it is likely that CAIDI also increases due to difficulty in fault locating.

These impacts can be mitigated by employing VGR as the backup scheme. In that case, the reliability performance under the communications-failure contingency is the same as normal operation for the VGR scheme previously discussed, resulting in similar SAIFI, SAIDI, and CAIDI outcomes.

The potential negative reliability impacts associated with backup protection are a factor that must be closely considered when implementing a CAT scheme. If it is desired to still have maximum reliability when the protection is in backup mode, the complexity of the implementation of the CAT scheme increases because the protection settings development is required for both the CAT protection settings and the backup VGR protection settings.

When CAT is combined with a FLISR system, it is expected that there will be improvements in both SAIFI and SAIDI. As described previously, FLISR will also cause MAIFI to increase as a tradeoff for turning sustained outages into momentary outages, reducing SAIFI. CAT schemes improve fault sectionalization by using high-speed communications between protection devices to rapidly identify and isolate the faulted segment, while FLISR automates the restoration of unfaulted portions of the feeder through alternate switching paths. As a result, fewer end users experience sustained interruptions. This combination generally produces greater improvements in SAIFI than FLISR alone because the outage is confined to a smaller portion of the feeder before restoration actions begin. Automatic restoration also reduces outage duration for unaffected customers, resulting in lower SAIDI.

CAIDI may also improve compared to a CAT-only implementation because FLISR restores service to most end users automatically, leaving only the faulted section requiring repair. Additionally, the rapid identification and isolation of the faulted section can also reduce restoration times by quickly directing crews to the faulted zone.

E. Impact of FRS

Under normal conditions, if deployed without FLISR, an FRS scheme provides fault indication and sectionalizing information. While the initial fault is still cleared by upstream protection devices, the additional visibility provided by the FRS reduces uncertainty regarding fault location and system conditions. This improved situational awareness can help operators and crews accelerate switching operations and restoration efforts, resulting in reduced outage durations and improvements in both SAIFI and SAIDI. Because the fault-clearing process remains largely unchanged from that of the VGR scheme, the impact on CAIDI and MAIFI are generally identical: CAIDI may see improvement while MAIFI is unchanged. MAIFI may increase if fuse-saving is used; however, this is a well-known and generally accepted consequence of fuse-saving schemes.

Consider a contingency in which a FRS fails to operate or loses communications. In this situation, visibility into the location and status of the faulted section is lost. Although the fault is still cleared by the primary protection system, operators

or FLISR applications may require additional investigation and switching activities to identify and isolate the faulted segment. This can increase restoration times and reduce the effectiveness of automated restoration schemes. As a result, SAIFI will worsen because more end users have experienced the outage. SAIDI and CAIDI may worsen due to the extended time required to locate the fault and restore customers. MAIFI will remain unchanged.

An FRS scheme without FLISR has little benefit. Isolation of the faulted zone and restoration of end users must be performed manually by a system operator, a process that can often take longer than 5 minutes. As a result, what would be classified as MAIFI events with FLISR becomes SAIFI events without. Therefore, when paired with FLISR, there are improvements in SAIFI and SAIDI equal to those of the VGR and CAT schemes, with the same possible increase in MAIFI.

CAIDI may also improve because the FRS fault indications help identify the faulted area similarly to VGR and CAT schemes, reducing patrol time and accelerating repairs.

X. CONCLUSION

Distribution protection has increased significantly in complexity as the number of devices has increased. This paper focuses on three known distribution protection schemes that, when combined with FLISR supervision, can improve reliability of distribution circuits. The goal is to assist the reader in choosing which scheme best suits their project by providing guidance on the advantages and limitations of each. There is no universal best scheme; rather, the factors discussed throughout this paper must be carefully weighed to decide which scheme best meets current and future needs. Utilities should consider not only current operational requirements but also future expansion, automation, and maintenance needs when selecting a protection strategy.

In summary, the VGR scheme is easiest to implement without a FLISR system and has the lowest complexity and fewest scalability requirements because it most closely resembles a traditional overcurrent protection scheme, in which all isolation and fault identification are performed locally. This is also the only scheme that can provide proper coordination without communications, which may be an important consideration in areas with unreliable radio or cellular service. Although protection is still limited by the normal factors of selectivity and sensitivity, many reclosers can be installed into small areas, vastly improving reliability over traditional protection schemes. Improvements in SAIFI and SAIDI are expected, while MAIFI may worsen. This is an easy tradeoff to make. CAIDI is likely to improve initially as fault locating becomes more accurate; however, those improvements will eventually plateau over time as faults are consistently isolated to the smallest area and number of impacted end users. Beyond that point, restoration speed is still dependent on the ability of the line workers to fix the problem.

CAT schemes are the most complex to implement, but they also provide the most standardization and the fastest clearing time improvements. These schemes are most cost-effective in urban, densely populated areas with short length circuits that

have high end user density, where the cost of necessary communications equipment is lower than in spread-out deployments. In such applications, backup protection for when communications are down becomes straightforward because all devices can be configured as a single VGR coordination group.

As circuit length increases, however, complexity of the backup scheme increases. If fully coordinated backup protection scalability is desired, the overall scheme may become more difficult than a VGR scheme. Reliability metrics should improve at similar rates to a VGR scheme except a CAT scheme will yield a better MAIFI improvement because upstream interruptions always occur from the device closest to the fault, rather than cascading down the circuit and tripping every device in line with the fault.

FRS schemes provide a hybrid level of complexity that sits between VGR and CAT schemes, but they offer no benefit without a centralized FLISR system. If a FLISR system already exists, these schemes can provide significant benefits with very little additional complexity. However, the dependency on FLISR also means that a reliable communications network is critical, which can result in higher initial setup cost and maintenance than either VGR or CAT schemes.

FRS schemes also offer the most flexibility and scalability due to the centralized intelligence, albeit at the cost of standardizing all devices with the same equipment and the setup and maintenance costs of the centralized intelligence. The improvements of SAIFI and SAIDI are identical to VGR and CAT schemes. However, MAIFI is expected to worsen because overtripping of zones is required.

Ultimately, the optimal scheme depends on the utility objectives, system characteristics, and long-term operational strategy. VGR requires the lowest upfront investment and offers the greatest benefit-to-cost ratio for many applications. CAT is best suited for densely populated feeders where communications infrastructure can be justified and maintained. FRS provides the greatest flexibility and scalability through centralized intelligence, but the centralized intelligence may mean higher implementation and maintenance costs. Therefore, the selection of a protection scheme should be based not only on present reliability requirements, but also on anticipated future system growth, operational needs, and automation goals.

XI. REFERENCES

- [1] J. Thorne, D. Nahay, C. Salo, J. Blair, and G. Ashokkumar, "Improving Distribution System Reliability With High-Density Coordination and Automatic System Restoration," proceedings of the 76th Annual Georgia Tech Protective Relaying Conference, Atlanta, Georgia, May 2023.
- [2] R. M. Cheney, J. T. Thorne, R. Van Singel, A. Hanson, C. Anderson, and J. Hughes, "Case Study: High-Density Distribution Coordination Using High-Speed Communications," proceedings of the 47th Annual Western Protective Relay Conference, virtual format, October 2020.
- [3] IEEE Std 1366-2022, *IEEE Guide for Electric Power Distribution Reliability Indices*.
- [4] IEEE Std C37.230-2020, *IEEE Guide for Protective Relay Applications to Distribution Lines*.
- [5] IEEE Std 242-2001, *IEEE 242 IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (IEEE Buff Book) (Color Book® Series)*.

- [6] IEEE C37.104-2022, *IEEE Guide for Automatic Reclosing on AC Distribution and Transmission Lines*.
- [7] IEEE 1547-2018, *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*.
- [8] IEEE C37.113-2025, *IEEE Guide for Protective Relay Applications to Transmission Lines*.
- [9] A. Stinskiy and S. Chanda, "Direct Transfer Trip (DTT) Leveraging Redundant Cellular Communication Channels," proceedings of the 75th Annual Conference for Protective Relay Engineers (CPRE), College Station, TX, 2022.
- [10] M. Boeding, P. Scalise, M. Hempel, and H. Sharif, "Evaluating the Latency Impact for Time-Critical Operational Technology Applications of Transitioning IEC-61850 GOOSE Operations to 5G," in IEEE 21st Consumer Communications & Networking Conference (CCNC), Las Vegas, NV, 2024.
- [11] T. Doshi, R. Sharma, and A. Rahiminejad, "Detection and Isolation of Broken Conductors in Power Distribution Systems: A Key Wildfire Mitigation and Public Safety Strategy," proceedings of the 72nd Annual Petroleum and Chemical Industry Technical Conference, Dallas, TX, September 22–24, 2025.
- [12] M. Kistler, F. Heleniak, C. Kennedy, and G. Maday, "Practical Experience With High-Impedance Fault Detection in Distribution Systems-Continued," proceeding of the 49th Annual Western Protective Relay Conference, October 2022.
- [13] N. Nakamura, M. Bundhoo, A. Rahiminejad, and D. Hou, "Fire Mitigation for Distribution," Schweitzer Engineering Laboratories, Inc., 2021.
- [14] NERC, "Characteristics and Risks of Emerging Large Loads," NERC, 2025.

XII. BIOGRAPHIES

John Thorne has more than 20 years of experience with Alabama Power Company, where he has served in various distribution engineering roles. His experience includes construction, protection, and reliability. He currently serves as the Power Delivery Test Lab team leader. He received his BS in electrical engineering from Auburn University in 2004.

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Andrew Hanson received his BSEE and BS in physics from Clemson University in 2015. Andrew joined Schweitzer Engineering Laboratories, Inc. (SEL), where he serves as a project engineer for SEL Engineering Services, Inc. (SEL ES) in Atlanta, Georgia. His work focuses on designing, developing, and deploying automation schemes for distribution networks.

Joseph Thomas is an associate engineer with Schweitzer Engineering Laboratories, Inc. (SEL). He earned a BSEE degree from Penn State University.