Power System Contingencies to Evaluate FLISR Systems

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***Abstract*—Utilities aim to improve the reliability of the electric grid to reduce economic losses, improve safety, and decrease the inconvenience caused to customers. Fault location, isolation, and service restoration (FLISR) technologies try to optimally reduce outage durations and the number of customers affected by outages. It is crucial that the implemented FLISR technologies address various contingencies that can occur in the system while maintaining the system within acceptable limits. At the heart of FLISR is a robust communication network that enables field devices to work in tandem. Losing a single device could impact the FLISR process. Hence, the control algorithm, communications network, and device settings for the FLISR system should be thoroughly assessed. This paper details the power system and communications contingencies that should be tested to analyze the reliability and performance of a new FLISR system. The paper describes the contingencies and expected response of a FLISR system through an example using a radial distribution network that was simulated using a hardware-in-the-loop (HIL) system with recloser controls connected to a centralized FLISR system and a mesh radio communication network. It explains methods to obtain expected restoration times for the example system, report the results for the example system, and analyze those results.**

I. Introduction

A traditional distribution radial circuit does not have adequate fault location, isolation, and service restoration (FLISR) capability to reconfigure energy supply to customers during outages and system abnormalities. This is primarily due to a limited number of switching devices on the circuit, which are used to isolate a fault, and the absence of a smart switch or recloser at the normal-open point, which would enable the restoration of load from adjacent sources [1]. In 2018, the average U.S. customer faced electrical outages for a total of approximately six hours with the majority of the outages occurring at the distribution level [2]. Not only are the numbers already high, but the trend also shows an annual increase in those numbers [3]. This has led to utilities vying for solutions and technologies that reduce outage times, lower the cost of restoration, decrease revenue losses to customers, and attract and retain customers. Indices described in the *IEEE Guide for Electric Power Distribution Reliability Indices* [4] are good markers that the industry frequently uses to evaluate reliability.

Distribution systems are effectively the final stage in the power transmission process, which begins at generation and ends at customers. An event occurring at the transmission or generation level is usually resolved using alternate feeders or modes of generation, but a problem in the traditional distribution system directly affects the power delivered to customers. Loss of power can have cascading effects, eventually leading to economic losses, equipment issues, and impacts on health and safety. The power industry seeks to reduce the inconvenience caused to customers by employing systems at the distribution level that operate to reduce outage duration and the number of customers affected. These systems are called FLISR technologies.

The first step in the FLISR process is fault detection and subsequent fault isolation. After isolation, the process of restoration begins, supplying power to customers who are not in the faulted zone but still affected by the fault. In typical distribution schemes, there are normal-open tie reclosers or remote-operated switches connecting one feeder to another. These tie points are sometimes available to transfer portions of the distribution line to different feeders. The goal is to ensure that a maximum number of customers have power restored without violating any operational constraints. The process should aim to maximize post-reconfiguration feeder margins and minimize the overall switching operations to reduce wear of the switching devices. Successful isolation and operation require dependable communication to field devices. In distribution systems without FLISR, actions taken to heal the distribution system are performed by human operators [5] or not at all. But with the increasing complexity of distribution networks, the industry is moving toward reliably automating the restoration process, helping reduce switching errors, and decreasing the time required to take corrective actions. Generally, fully automated FLISR technologies consist of communication networks, recloser or breaker systems, data acquisition and processing systems, and centralized or regional FLISR control. The devices and technologies work in sync to reduce the size and duration of power outages. Fault location and isolation helps locate impacted sections, facilitating quicker repairs, and power can be supplied to the customers in the areas affected by the trip but not in the faulted zone, thus reducing outage durations.

During a permanent fault on a distribution system with FLISR enabled, the relay upstream of the fault detects the fault and starts timing. After going through its reclosing sequence, it eventually locks out. Then the FLISR system's job is to open any isolation device to isolate the faulted line section. This information from the relay is communicated to the distribution automation controller(s) (DAC) via the communication devices. The controller signals the relay(s) downstream of the fault to open and isolate the fault. Then the controller takes an account of the statuses of the devices in the system, as well as the operational limits, and comes up with a restoration plan for the downstream affected customers. The controller sends messages to devices that may include the need to change their statuses to open or close as needed to isolate faults and restore loads. After receiving these signals, the devices operate accordingly, ultimately transferring the load (customers) downstream of the fault to adjacent circuits and restoring power to the region.

Other contingencies can arise, for example, if there is a loss of power to a feeder (or multiple feeders at once) due to a transformer outage, transmission loss, or storm, and customers served by the feeder will experience an outage. The customers should be transferred to an adjacent feeder, provided the adjacent feeder is capable of supplying the additional load, i.e., the additional load should not violate the feeder's loading limits. The transfer of load to adjacent circuits without regard to the feeder load limits may result in overloading a feeder. In such a situation, more than one feeder may be used to restore the load (after sectionalizing the outage region into multiple areas in order to maintain a radial restoration solution). If a complete restoration solution cannot be found, then some load may be left de-energized.

Communication devices can also face issues that hamper the goal of restoration. These devices need to satisfy the bandwidth demands during a fault scenario. If the network is burdened, messages can get dropped and may not reach their destination, jeopardizing the restoration process. Sometimes, the communications network could require reconfiguration to complete the restoration process.

This paper describes a distribution-level mesh network that provides communications to protective devices across four feeders that feed various loads in the system. There are ten reclosers and corresponding recloser controls that communicate to a FLISR controller via dedicated radios. Section II describes the motivation to test FLISR systems. Section III details the common components that are part of a FLISR system. Section IV describes the contingencies based on the aforementioned motivations and components. The results for the various tests performed are then analyzed and detailed in Section V. Section VI concludes the paper, explaining our findings as well as applications and benefits of the implemented FLISR system.

II. Motivation for Testing FLISR Platforms

A FLISR system can be a great asset for utilities wanting to restore power efficiently and quickly to customers affected by an outage. Because of the number of inputs, number of outputs, various connections, and the complex decisions a FLISR system makes, a lack of testing can lead to a wide range of operational failures. Impacts can range from inefficient operation to hazardous situations that endanger personnel safety.

Tuning communications parameters plays a significant role in efficient operation of a FLISR system. Bandwidth on communications networks is generally limited, and some communications options can have increased maintenance cost associated with the amount of bandwidth used. Parameters such as protocol selection, polling intervals, polling modes, datapoint deadbands, and intentional time delays can dramatically impact restoration times and bandwidth utilization on the communications network. While FLISR systems may appear to detect events, isolate faults, and restore loads correctly, changes to communications parameters can impact operating speed, turning momentary outages into sustained outages or increasing data charges by an order of magnitude. Testing provides automation, control, protection, and communications personnel an opportunity to optimize settings to result in a balance of high reliability and low maintenance costs.

Testing can also provide insight to behaviors of FLISR control algorithms. A wide variety of FLISR control algorithms are available, with various settings and features enabled. Some features are enabled through the population of optional data inputs from the field, while others are explicitly enabled through settings. Line loading and capacity limits are parameters that some FLISR control algorithms consider, and others do not. Certain algorithms do not consider capacity limits and line loading, such as high-speed transfer schemes that prioritize speed of restoration but require capacity on alternate feeds to be reserved for the load that will be transferred. Testing with FLISR schemes on model power systems allows a wide variety of loading conditions to be tested that may represent daily variation in load, seasonal load, or forecasted load growth for the region. These tests can provide insight regarding how FLISR algorithms may use load data. Test scenarios with loading conditions and fault conditions that result in significant load loss but limited transfer capacity can help identify if algorithms are capable of splitting loads and using multiple alternate sources. This capability is valuable to prevent overload conditions on alternate sources. Overloading alternate sources due to FLISR scheme operation results in tripping of alternate sources and increased outages compared to the initial fault event.

Any system designed to automatically transfer loads to alternate feeds not only introduces a risk of overloading equipment but introduces a safety risk to personnel that should be thoroughly tested. Line crews rely on safety tagging to reduce arc flash energy exposure by making protection trips faster, disabling reclosing, and blocking remote closing. Problems in field device logic settings, data maps, and communication addresses can result in FLISR control algorithms that incorrectly close into line segments and equipment that are tagged for the safety of line crews. Careful testing, documentation, and training of FLISR systems improve personnel safety and the use of FLISR systems.

III. FLISR System Components

Decision-making for simple loop schemes and transfer schemes can be performed in edge or field devices, but as distribution feeders are complicated by loading capacity restrictions, increased sectionalizing capabilities, and an increased number of alternate sources, a FLISR system must consider increased amounts of data from field devices on automated feeders as well as adjacent feeders. Making decisions at a feeder level, station level, area level, or regional level is required to maximize the number of customers automatically restored following a fault and to prevent overloading the equipment during restoration.

A. DAC

A DAC is a centralized controller that makes use of load data, feeder topology, through-fault targets, remote controls, and electronic tagging to enable FLISR on a feeder network. Before a fault occurs, a DAC polls field devices on a feeder network to identify topology, loading, and available capacity of the feeder network and its feeder segments. Immediately following the detection of an event using voltage elements, lockout statuses, or through-fault targets, the DAC updates its knowledge of the topology and alarm statuses by polling all field devices to identify the locations of faults, solutions to isolate faults, and switching to restore as many loads as possible without overloading system elements [6].

B. Field Devices

The DAC can use data from a wide variety of field devices, including breakers, reclosers, motor-operated switches, and sectionalizers [6]. In our test scenarios, we use reclosers on overhead distribution feeders and tie points, but these devices can be substituted based on existing infrastructure or utility construction standards. Controllers for field devices must include these key features to operate with the DAC: battery backup, remote operation, load measurement, and through-fault detection. Additional functionality is enabled with voltage measurements.

Field devices must have the ability to measure current, so they can measure loads under normal conditions and detect through-fault current during events. Through-fault detection typically uses fixed fault current level detection thresholds and latches to indicate that through-fault current was detected passing through the field device. To ensure old data are not used to determine fault locations, through-fault current latches are typically either reset by the DAC or reset automatically following a two-minute timer. The DAC uses the assertion and deassertion of through-fault latches on radial feeders to identify the two switching devices closest to the fault: the last switching device with an asserted through-fault latch and the first switching device with a deasserted through-fault latch.

Once the switching devices closest to the fault are identified, the DAC uses remote operation of field devices to isolate the fault. Isolation of the fault allows the surrounding feeder segments to be restored through alternate sources without exposing alternate sources to the fault. Ties to the alternate sources are then closed as capacity is verified to ensure alternate sources are not overloaded by the switching.

Load data gathered prior to the event are used to estimate the load that is restored using alternate sources. Field device controllers must measure and report these load data to the DAC periodically so the DAC can estimate load distribution on all switchable feeder segments on the system prior to any events. Load data are used to continuously calculate capacity margins for all sources under consideration during restoration stages.

For the DAC to retrieve all necessary data and remotely operate all devices following an event, controllers for field devices must have batteries to power controllers, communications, and operation of the switching devices. Controllers are generally powered primarily by alternating current (ac) power from the line, but the ac power is frequently lost during events that require DAC operation. Following the loss of ac power, batteries are typically sized to provide more than four hours of run time for all controllers and communication equipment while reserving sufficient energy to operate switching devices at the end of the designed battery run time.

C. Communications

The communications network linking field devices with the DAC is vital to the effectiveness of a FLISR system. The communications can be implemented using a combination of various fiber optics and wireless technologies. Fiber optics have significant range and reliability advantages but also have considerable initial costs. Wireless technologies are attractive for relatively low initial installation costs but can be limited based on path obstructions and range. Mesh radio improves upon simple wireless technologies, allowing communications to be repeated around obstacles and extended significant distances. Radios can be organized into tiers with the highest tiers communicating directly to the collector radio and repeating signals to and from lower radio tiers that are unable to communicate directly to the collector, as shown in Fig. 1. A field device far from the collector may communicate through several tiers of radios or through several radio hops with the maximum number of hops limited by the increased latency introduced by each hop. A radio network can increase resiliency of the communications to distant devices by locating radios to provide multiple communication paths from every field device to the collector radio and DAC.

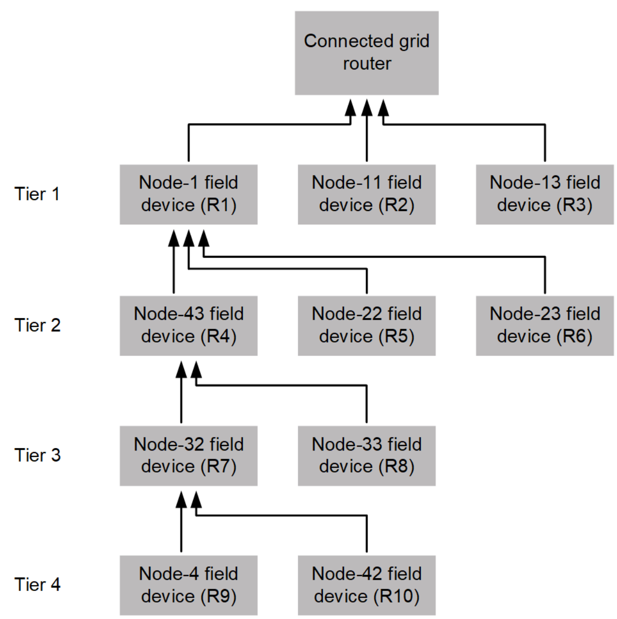

Fig. 1. Normal communications network topology.

When considering the reliability of a FLISR system, fault tree analysis is a valuable tool to identify major contributors to system unavailability [7]. The batteries that typically power controllers and communications equipment in field devices have increased maintenance and reduced replacement intervals compared to the other components. On a radial distribution feeder, the loss of a battery can result in miscoordination of time-overcurrent coordinated devices, but on a FLISR-enabled system, the resulting loss of communications can increase the number of customers impacted by an extended outage by an order of magnitude because it prevents FLISR from detecting events or operating switching devices. The importance of battery systems, battery health monitoring, and battery maintenance on the mesh communications system and the use of redundant communications paths must be considered in the testing of FLISR systems.

IV. Test Scenarios to Evaluate FLISR Platforms

The test system considered in this paper is fed through four feeders to loads located in the ten segments shown in Fig. 2. The default network topology of the system tested is illustrated in Fig. 1 with four hops. This topology was chosen as a test system because it is a good representation of a typical mesh system. In addition, multihop wireless networks with one or more intermediate nodes can improve connectivity and extend the coverage of a network for the test system [8]. In the normal state, Feeder Breakers 1–4 (CB1–CB4 in Fig. 2) are closed. Reclosers 1, 3, 6, 7, 9, and 10 (R1, R3, R6, R7, R9, and R10 in Fig. 2) are normally closed, and Reclosers 2, 4, 5, and 8 (R2, R4, R5, and R8 in Fig. 2) are normally open. The system voltage is at 12.47 kV, and the load demand can be varied. The segments are energized as follows:

- Segments 1, 2, and 3 are energized through Breaker 1.
- Segment 4 is energized through Breaker 2.
- Segments 5, 6, and 7 are energized through Breaker 3.
- Segments 8, 9, and 10 are energized through Breaker 4.

This system was modeled in a real-time simulator software to establish HIL functionality.

A direct Distributed Network Protocol (DNP3) Ethernet connection using the functionality available in the real-time simulator system allowed the analog quantities and statuses from the simulated sources and feeder breakers to be passed to the DAC, as well as control signals from the controller to be passed to the feeder breakers.

These analog and digital input quantities are considered substation data and do not pass through the mesh radio network in the field, and the same was replicated for our simulated system. Each recloser in the system was controlled by a recloser control. The reclosers were simulated in the real-time simulator, and the generated analog and digital quantities were sent to the recloser control inputs. The recloser control communicated with the DAC using DNP3 over User Datagram Protocol (UDP) through the mesh radio network. UDP is used instead of Transmission Control Protocol because of its efficiency, simplicity, and speed.

To determine the resulting customer outage durations for the loads that were restored by the test FLISR system, time-stamped voltage data from the recloser control were collected and analyzed. The outage duration from each test scenario and from each communication configuration are documented and compared in this paper.

Different communication setups were tested to determine differences in modulations, polling intervals, and unsolicited messaging. One of the tests involved orthogonal frequency-division multiplexing (OFDM) modulation with an 800 kbps data rate. OFDM modulation was used with various polling intervals and unsolicited messaging settings. Polling intervals of 10 seconds, 60 seconds, and 120 seconds were evaluated, as shown in Table I. The most aggressive polling expected on the mesh radio network was the 10-second poll interval without unsolicited messaging (Case I). Note that it is not recommended under 10 seconds on mesh systems. The mesh radio modulation was changed from OFDM to binary frequency shift keying (2-FSK) for Case IV, reducing the network bandwidth from 800 kbps to 150 kbps. The 2-FSK tests were performed with only DNP3 UDP traffic on the mesh network because fault isolation and restoration performance were determined to be unreliable using 2-FSK with event report collection and relay settings collection performed via Telnet. For mesh reconfiguration, the network was then returned to OFDM modulation, and the mesh network was modified, which is discussed later in Test Scenario 5.

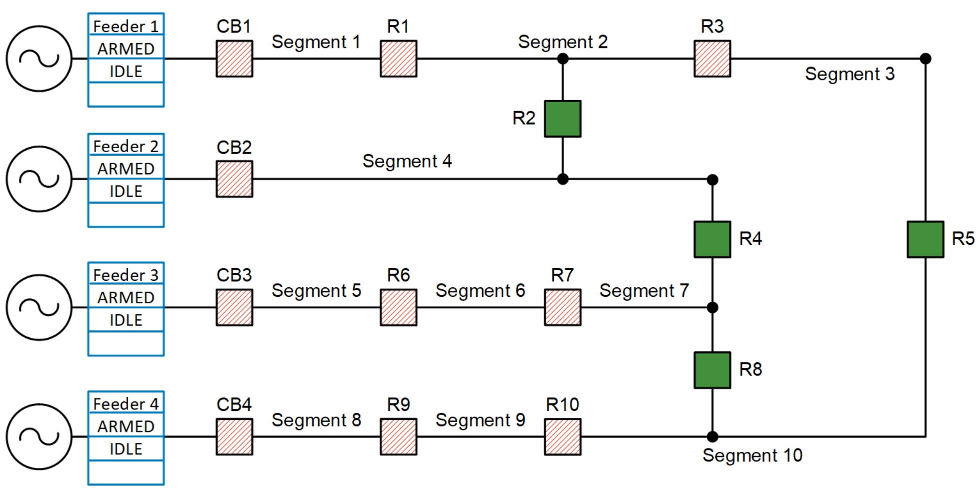

Fig. 2. Hardware-in-the-loop (HIL)-tested distribution circuit network one-line diagram.

TABLE I
COMMUNICATION SETUPS

Case	Modulation	Poll Interval (s)	Unsolicited Messaging
I	OFDM	10	Off
II	OFDM	60	On
III	OFDM	120	On
IV	2-FSK	120	On

The contingencies tested are described as follows:

A. *Test Scenario 1 (Base Case)*

This scenario represents the simplest FLISR operation test possible, involving the minimum number of field devices, simplest communications, fewest switching operations to isolate faults, fewest switching operations to restore loads, and no capacity restrictions. In complex systems, starting with the simplest test scenario allows evaluation of the most basic operations. When problems arise in the most basic test case, troubleshooting is simplified by eliminating the number of variables and components that need to be analyzed. Our base case involved minimizing the number of mesh radio hops, as shown in Fig. 1, to restore a load based on the system requirements described in Sections II and III. This fault scenario involves applying a fault between CB1 and R1, as shown in Fig. 3. CB1 trips and locks out for the fault, causing the loads between R1 and R3 and the loads between R3 and R5 to drop. The fault must be isolated by tripping R1 in order to restore power to the loads. All Feeder 1 load beyond R1 is transferred to Feeder 2 with the minimum loading by closing R2, as shown in Fig. 4. The restoration time is based on the time between the CB1 trip and the R2 close. Note that the DAC is not allowed to do anything until a protective device locks out. Therefore, most of the time, the DAC is sitting, waiting for lockout.

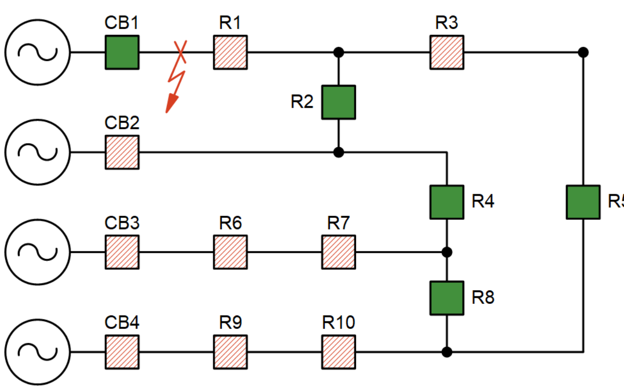

Fig. 3. Test Scenarios 1 and 2 outage.

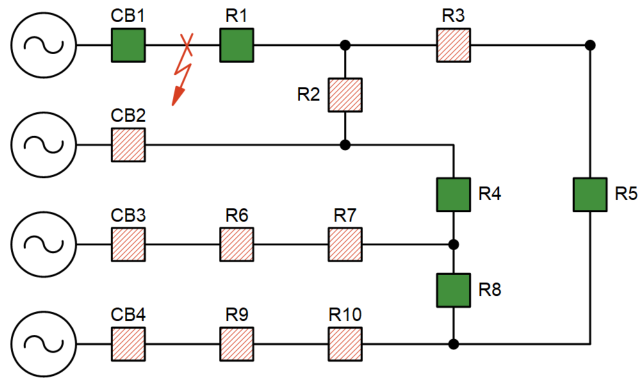

Fig. 4. Test Scenario 1 restoration.

B. *Test Scenario 2 (Evolution of the Base Case)*

Compared to Test Scenario 1, Test Scenario 2 is an evolution of Test Scenario 1 with a couple of additional conditions that complicate the expected response. The fault location is the same as Test Scenario 1, but increased loading, capacity restrictions on adjacent feeders, and involvement of multiple tiers of communications equipment to connect field devices far away from the connected grid router stress the algorithms and communications infrastructure. Complexities associated with this scenario can be removed and reapplied, creating additional variations to this scenario to isolate components and algorithms during troubleshooting, if unexpected behaviors are observed.

Loading is increased on Feeder 1, preventing the entire load from being transferred to either Feeder 2 or Feeder 4. The load is split according to the feeder capacity by tripping R3. The load between R1 and R3 is allowed to be transferred to Feeder 2 using R2, and the load between R3 and R5 is transferred to Feeder 4 through R5, as shown in Fig. 5. The tripping of R3 and closing of R5 yields the maximum number of mesh radio hops between the recloser and the DAC, as shown in Fig. 1. The maximum number of hops and load splitting constitute a FLISR with a centralized DAC scheme, as described in Sections II and III. The restoration time is based on the time between the CB1 trip and the R2 and R5 close. The tripping of R3 indicates a successful operation.

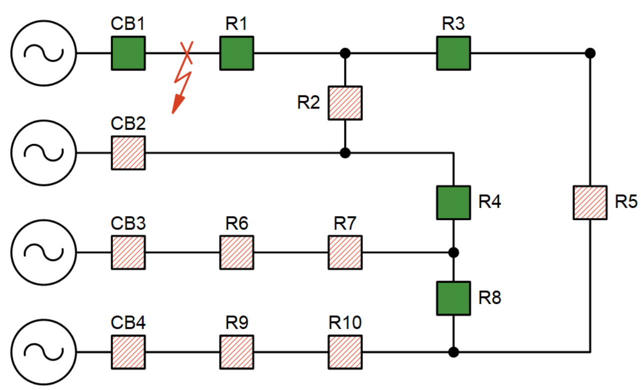

Fig. 5. Test Scenario 2 restoration.

C. Test Scenario 3 (Wide-Area Outage)

Wide-area outages can originate from events on the transmission system or within a substation. Loss of a transmission line or substation power transformer can result in loss of voltage on multiple feeders without any direct trip or lockout indication on field devices monitored by a FLISR system. The practice of manually transferring loads from three or more feeders onto a single feeder breaker is virtually never performed because the associated risk of overloading equipment already under peak load is too high. In addition, having advanced restoration algorithms and light loading associated with off-peak energy consumption while using automation to quickly and continuously reevaluate loading conditions can enable extreme restoration sequences during times when field switching personnel have longer response times due to reduced staffing levels and call-out procedures.

These wide-area outages are simulated by disconnecting the source voltage connected to CB2, CB3 and CB4, as shown in Fig. 6. FLISR's goal is to maximize the number of customers that can be re-energized without overloading the CB1 feeder. The DAC will recalculate after the addition of a load to ensure that the feeder can close the next normally open recloser without overloading the feeder. The main benefit of this transmission event is to showcase the ability to limit the number of customer outages as much as the available feeder can sustain. CB1, CB2, and CB3 are tripped, and three out of four of the normally open reclosers must be closed for the load restoration, as shown in Fig. 7. The restoration time is based on the time between the loss of the source voltage to the time when the last of the three reclosers is closed.

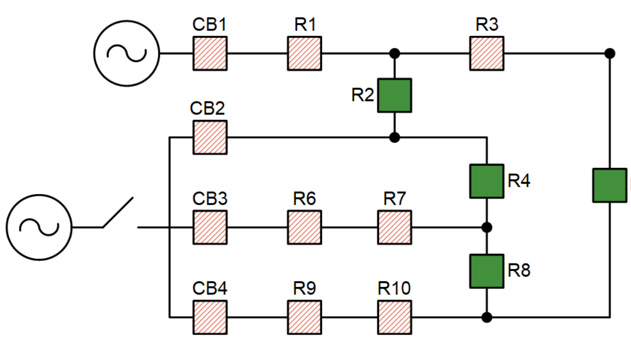

Fig. 6. Test Scenario 3 outage.

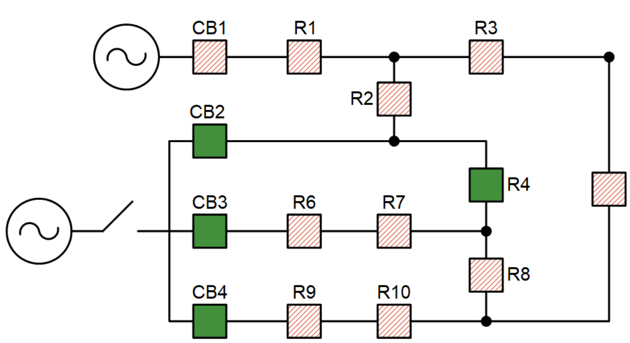

Fig. 7. Test Scenario 3 restoration.

D. Test Scenario 4 (Miscoordination)

Sometimes, a recloser control may have been set incorrectly, set to switch mode, or set to a slower alternate curve setting because of feeder switching conditions. This miscoordination is simulated by turning off the tripping of overcurrent elements in R6. The test scenario involves applying a fault between R6 and R7, resulting in tripping of CB3, as shown in Fig. 8. Here, CB3 miscoordinates with R6. R7 must be tripped to isolate the fault before the restoration process. CB3 and either R4 or R8 must be closed to restore power, as shown in Fig. 9. The restoration time is based on the time between the CB3 trip and the R4 or R8 close operation.

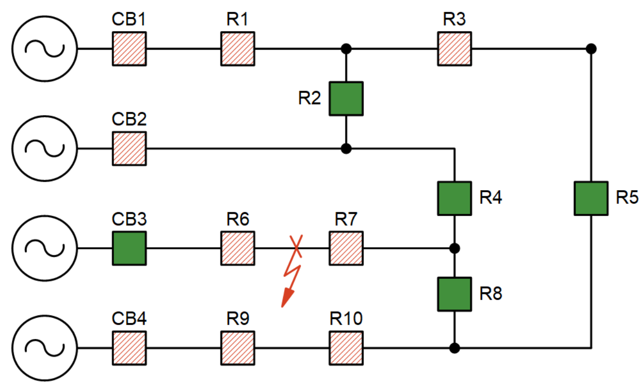

Fig. 8. Test Scenario 4 outage.

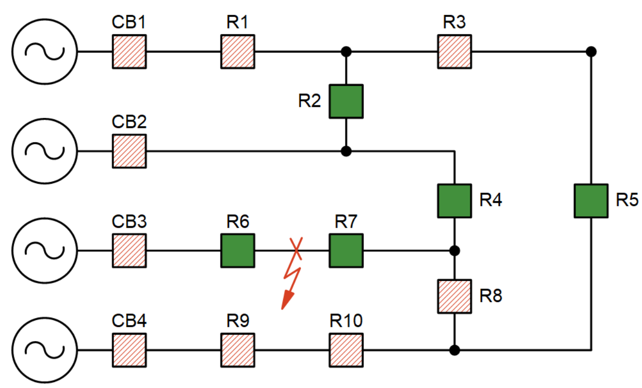

Fig. 9. Test Scenario 4 restoration.

E. Test Scenario 5 (Mesh Reconfiguration)

A review of the communications associated with Test Scenario 4 shows none of the involved devices has direct communications with the collector; all must communicate through an upper-tier radio. When this occurs, the mesh can be designed to allow field devices to communicate on multiple paths. This is important when considering that the reliability of the radios on upper tiers is dependent on the availability of the battery. Faults on the distribution system can sag the ac voltage on the substation bus and adjacent feeders, resulting in reset or restart of radios and field devices with bad batteries.

Test Scenario 5 uses a fault between R6 and R7, similar to Scenario 4, to evaluate the ability of the FLISR system to reconfigure the mesh for a loss of an upper-tier (Tier 1, Node-1 in Fig. 10) radio. The parent node, Node-1 (tied to R1), in Fig. 1 is turned off, which forces the child nodes and the mesh network to reconfigure during the fault event. The final mesh network topology would look like the one shown in Fig. 10, and the final electrical network topology would resemble the one in Fig. 11. The FLISR operation should be unaffected by the permanent loss of R1 data.

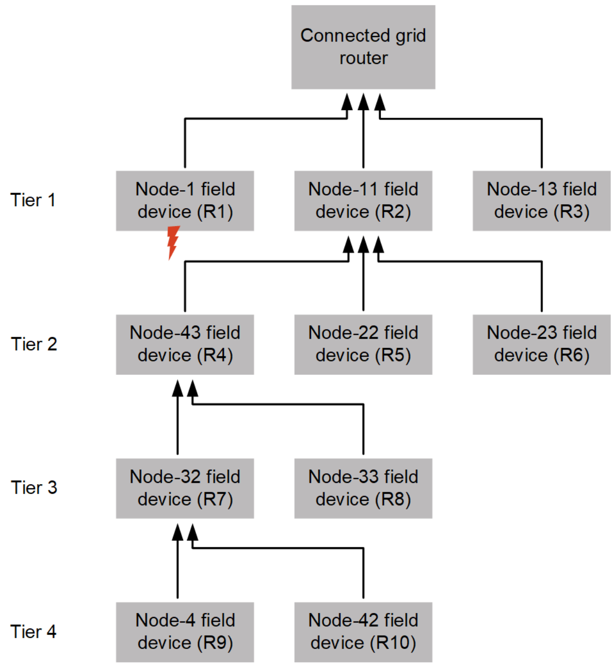

Fig. 10. Test Scenario 5 final network topology after mesh reconfiguration.

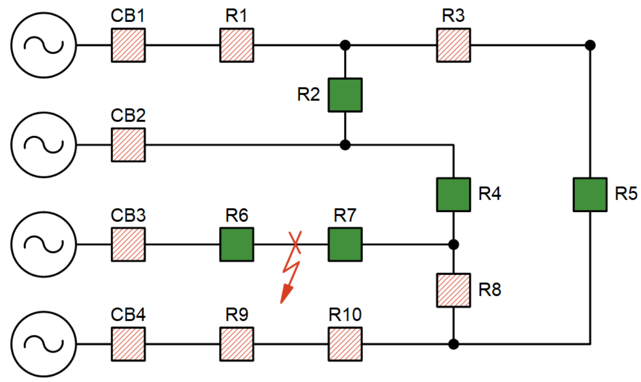

Fig. 11. Test Scenario 5 restoration.

V. Results

Table II shows the outage duration for different fault scenarios described in the previous section. For Test Scenario 1, voltage element time stamps in R3 are evaluated to determine the total outage duration. Comparing Table I and Table II, we can observe that the outage duration shortens by enabling unsolicited messaging compared to only polling. Also, when we enable unsolicited messaging, there is minimal impact to the outage duration by poll interval or modulation type. The exact percentage difference is also shown in Table II with Case I (which has the largest restoration time) as the base case except for Test Scenario 5, where Case II is the base case.

Similar to Test Scenario 1, voltage element time stamps in R3 are evaluated to determine the total outage duration shown in Table II for Test Scenario 2. We can observe in Table II that poll interval and unsolicited messaging made a significant impact to the outage duration, especially in Case III and Case IV.

TABLE II
RESTORATION TIMES FOR DIFFERENT TEST SCENARIOS

Case	Test Scenario 1 (s)	Test Scenario 2 (s)		Test Scenario 3 (s)			Test Scenario 4 (s)	Test Scenario 5 (s)
		Segment 2	Segment 3	Feeder 2	Feeder 3	Feeder 4		
I	23.186 (0%)	23.544 (0%)	19.920 (0%)	32.169 (0%)	53.451 (0%)	41.297 (0%)	29.002 (0%)	Not tested
II	19.378 (–16%)	20.428 (–13%)	20.420 (3%)	24.870 (–23%)	31.182 (–42%)	27.202 (–34%)	20.128 (–31%)	181 (0%)
III	16.653 (–28%)	14.591 (–38%)	14.603 (–27%)	25.452 (–21%)	38.376 (–28%)	28.773 (–30%)	21.070 (–27%)	164 (–9%)
IV	18.318 (–21%)	15.002 (–36%)	15.077 (–24%)	28.181 (–12%)	43.018 (–20%)	32.156 (–22%)	15.212 (–48%)	Not tested

For Test Scenario 3, voltage element time stamps in R4 and R8 are evaluated to determine the total outage duration. We can observe in Table II that enabling unsolicited messaging resulted in better outage duration compared to only polling. With unsolicited messaging enabled, poll interval has little to negligible impact on the outage duration, and OFDM modulation provides only slightly improved performance over 2-FSK. As shown in Table II for Test Scenario 3, the benefit of enabling unsolicited messaging over polling is increased when multiple restoration actions are required.

For Test Scenario 4, voltage element time stamps in R4 are evaluated to determine the total outage duration. Similar to the previous scenarios, enabling unsolicited messaging resulted in shorter outage durations than only polling. Poll interval, however, has little to negligible impact on the outage duration with unsolicited messaging enabled. The performance improvement that was achieved using 2-FSK may be due to reduced bandwidth utilization.

Similar to Test Scenario 4, voltage element time stamps in R4 are evaluated to determine the total outage duration for Test Scenario 5. The network reconfiguration was achieved within two minutes. However, the recognition of the fault by the DAC following the communication outage is based on the polling interval and unsolicited message retry intervals (60 seconds). The difference in outage durations shown in Table II does not represent any significant difference in performance and can be attributed to the unsolicited message retry interval.

VI. Conclusion

Due to increasing complexity of the distribution system, where traditional protection may fail, and to reduce human errors, self-healing FLISR technologies are increasingly being implemented. This necessitates thorough testing and analysis of these FLISR platforms to confirm that the operational strategies performed are adequate. The control logic, communications, protection devices, and device settings form the basis of FLISR technologies and should be qualified before the system goes into operation.

This paper presents contingencies tested that are specific to one FLISR system, one distribution feeder network topology, and one type of communications network. The system simulated in this paper performs all the necessary steps to detect, isolate, and restore service during abnormal conditions. As this paper demonstrates, when implementers of FLISR systems identify these contingencies for other systems to be tested, for the distribution network topologies, and for communications mediums, they must involve a wide variety of disciplines to identify the contingencies that adequately test their own FLISR systems. Disciplines may include:

- Operations: The simplest tests, such as Scenario 1, are effective for testing supervision conditions and gaining confidence in the FLISR system by operations personnel. These simple tests verify proper mapping of data points, effectiveness of blocking and enabling conditions, and speed of operation for most conditions.
- Planning: Loads are continuously changing due to growth in the community. Increasing loads combined with limited equipment capacity reduces options for transferring loads between feeders. Without sophisticated algorithms that consider loading and equipment capacity, FLISR systems can increase customer outages by overloading alternate feeders. Scenario 2 demonstrates the proper response when loading and equipment capacity must be considered.
- Transmission and substation: Single-line or equipment outages at higher voltage levels can result in widespread outages of multiple feeders on the distribution system. Scenario 3 describes one of many possible behaviors.
- Reliability: Increasing the number of supervisory control and data acquisition (SCADA)-enabled switching devices on distribution feeders is a common initiative for improving distribution reliability, but maintaining coordination of large numbers of equipment, especially with inverse-time overcurrent curves, reclosing schemes, and sectionalizing schemes, is extremely difficult, particularly when feeders are automatically reconfiguring. FLISR schemes must be able to identify, alarm for, and recover from miscoordination to maximize reliability, as demonstrated by Scenario 4.
- Communications: Test Scenario 5 simulates loss of a communication device, which prompts the FLISR system to reconfigure the communication network in order to respond to an event. The communications team not only provides various communications-related contingencies to test the FLISR system against but also narrows down the choices for the communication medium, modulation type, polling details, etc.

Hence, control and automation teams implementing FLISR schemes must closely collaborate with many other disciplines to identify and test situations that avoid unsafe switching scenarios, overloading of equipment following transfer of load, and extended widespread outages for customers when unusual restoration switching is possible. This collaboration also ensures acceptance by operations personnel and reliability of operation even when communications and coordination are not ideal. The understanding gained by all parties through this collaborative testing results in continued acceptance, use, and maintenance of FLISR systems for many years.

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IX. Biographies

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