Site acceptace testing of a Duke Energy automation project utilizing a simulation based test approach

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Abstract— **As part of a proof of concept for future distribution schemes, Duke Energy has completed the second phase of a project on a distribution system feeder for the Raleigh Central Business District underground system. The feeder consists of two radially operated 12kV underground circuits. Solid dielectric vacuum switches with integrated visible break were installed in nine network vaults during phase 1 of the project. To achieve high electric service availability for the central business district, a communications-assisted, high-speed protection system was developed. Its unique communication architecture utilizes IEC 61850 GOOSE messaging and serial based communications in parallel, enabling the relays to interrupt, isolate and restore power via the nine vault switches once the project is completed.**

An important aspect of the acceptance test was testing the protection and control scheme. In this scheme 18 relays and two communication technologies are working together as a system. Due to the interdependency of the network protection system and its components, it was critical to test every component as part of a system. Multiple acceptance criteria were defined by describing the initial state of the power system, the incident fault and the expected system state after the interruption, isolation and restoration of the system had taken place. The acceptance criteria were directly configured into the test environment by using a power system model that calculated the test set outputs. A single PC controlled a total of nine test sets, simultaneously injecting all signals according to the selected test case.

A requirement for placing the protection system into live operation after installation was the completion of field site acceptance testing. Site acceptance testing included testing the individual switching nodes during commissioning followed by a series of simultaneous network system response testing involving all of the switches. This paper discusses the network installation, site acceptance test planning, testing contingencies discovered during planning, and the outcomes of the site acceptance testing.

Keywords—system testing, GOOSE, IEC61850, acceptance testing, automation

I. INTRODUCTION TO PROOF OF CONCEPT

The downtown Raleigh automation proof of concept is an effort by Duke Energy to develop, test, install, operate, and monitor a high reliability switching solution to promote the safe and reliable delivery of electric service to customers in high density zones. Duke Energy regularly seeks to improve the reliability and quality of service to its customers through various initiatives, including technology development and proofs of concept. Proofs of concept allow Duke Energy to perform a limited scale deployment of a technology solution, while developing in parallel the required business work processes, change management, training, and other required artifacts that allow Duke Energy to more fully evaluate the feasibility of implementing the technology at the utility.

Duke Energy has served the Raleigh, NC area for over 100 years, initially providing both electric and gas service as well as operation of electric streetcar transportation. Over the years, Duke Energy transitioned out of the gas and electric streetcar business, but continued to be the primary electric provider to the city. The city developed around a planned center core designed by surveyor William Christmas, with its primary business district developing south of the centrally placed state capital along Fayetteville Street: named for one of the four cities considered as an alternate state capital to Raleigh [Raleigh]. Duke Energy provided electric service to this growing area via overhead electric radial lines originating from its power plant and substation on the north-west side of town. Over time, the radial circuits were migrated underground to serve the central business district in a series of vaults, with manual switching points between circuits. Service voltages were standardized in the central city at 12kV line to line, with medium electric voltage serving a series of step down transformers within the vaults to serve customer load. Load growth also led to the establishment of four primary retail substations at the four corners of the city, with varying high tension transmission voltages at 230kV and 115kV. Engineering planners increased the reliability of the downtown service area over time by introducing diversity to various circuits at manual switching points by sourcing each circuit supplying an area from a different substation. Circuits were designed with adequate capacity to carry adjacent circuits if required. In the late 1970s and early ‘80s, Duke Energy installed a series of SF6 gas filled manual switchgear with local manual operators to allow for manual switching between adjacent vaults. The primary circuit way switches were rated at 600 amps each with tap ways serving step-down transformers rated at 200 amps each. Current limiting fuses were placed in series with each tap circuit serving a transformer to provide a means of protection and isolation in the case of an inadvertent event. Circuit breakers in the substations served as primary circuit protection and isolation devices, with the current limiting fuses serving as secondary protective devices to each of the taps. If a primary circuit event occurred, electricity to all customers on the radial circuit would be interrupted. To restore service for an extended event, manual switching would be performed at the vault level by local technicians. This arrangement served the Raleigh business district well for over 30 years, resulting in a low frequency of events and power loss. Over time, the level of customer load and density has increased. As greater levels of business and economic output have become reliant on dependable electric service, customer expectations for improved reliability of service have also grown. Due to these factors, as well as a need to replace aging equipment in these areas, Duke Energy launched a proof of concept effort to better understand and develop greater expertise regarding automation and telecom technologies and explore opportunities to provide high speed automation switching solutions for distribution.

The requirements for the proof of concept included the following:

1. System must be able to respond on its own to isolate an event.
2. System must have the ability to be flexible in its design to allow for the meeting of multiple use cases for operation and circuit configuration.
3. System must have the ability to overcome the failure of primary systems, including communications, switchgear, or automation relays.
4. System must be able to isolate a fault and restore the maximum number of customers within a predetermined time frame
5. Operation of the system must allow for either remote or local operation by an operator from outside of the enclosed space environment to promote the safety of the employees.
6. System must allow for reconfiguration to its normal state with a single remote command.
7. System must allow for remote designation of new normal state.
8. System must be self-contained, not reliant on a single automation controller or other single point of failure component.
9. Hardware design must allow for watertight conditions and the ability to isolate the control from the switch components.

Duke Energy selected a location in downtown Raleigh near its North Carolina Regional Headquarters for the proof of concept. The proof concept for the automation and telecom control system was incorporated into an existing underground switchgear replacement project in the area. The proposed test bed consisted of two radial circuits running through nine separate vaults from two separate sources with a normally open switching point in the middle of the loop. One of the high-tension (transmission) sources was rated at 115kV line to line and the other high-tension (transmission) source was rated at 230kV line to line. Due to the phase rotation of the two high-tension sources and the concern for bulk energy transfer over the medium voltage system, the system was designed to be operated in a normally open state. All of the vaults were located within a two city block radius of each other.

Duke Energy selected the switchgear vendor as the primary system designer for the automation system with Duke Energy providing design input. For the telecom design, Duke Energy utilized its own internal telecom engineering team and telecom designs previously deployed by Duke Energy Transmission teams. For testing the system, the switchgear vendor and Duke Energy partnered with a major electrical testing company with the capability of testing the entire system at once using simulated inputs/outputs while focusing on actual automation control system response. To reduce the risk of service interruptions to utility customers during the proof of concept effort, Duke Energy performed extensive lab and factory-based system and component tests prior to placement in the field. System level testing was performed at the factory and in the field prior to live operation. The factory testing was the subject of a previous paper while this paper will focus on the field testing [Keller et al.].

This paper will focus on the overall requirements and design of the automation system and its related hardware, discuss the concepts, development, and layout of the system-wide acceptance testing, the execution and results from the site acceptance testing, and lessons learned in the process.

II. HARDWARE DESIGN

The solid dielectric switches and controls used in this project are installed below ground and thus may be prone to contact with water during storms. To minimize the number of designs and to increase flexibility when replacement units are needed, all switches and controls were designed to be submersible, meeting the NEMA 6P standard. NEMA 6P standard provides for the cabinets “to provide a degree of protection with respect to harmful effects on the equipment due to the ingress of water (hose directed water and the entry of water during prolonged submersion at a limited depth)” [NEMA]. This improves the storm hardness of the system; however, because these controls are designed to be located inside sealed and bolted cabinets, access to the controls for testing and maintenance is much more difficult. To overcome this challenge, the control components were separated into two cabinets: one to connect and house the relays and the other to interface between the relays and the switch. Connectorized, submersible cables were used to easily and securely connect between the two cabinets, communication equipment, the control pendant and the batteries. The interface cabinet includes test switches which can be used to isolate trip signals and to inject voltage and current from a test set, however, these are behind the bolted-on lid of the cabinet. To increase ease of testing and to reduce the number of times the lid must be opened, Duke requested that the switchgear manufacturer investigate a method to more easily isolate the switch and connect the relays to a test set.

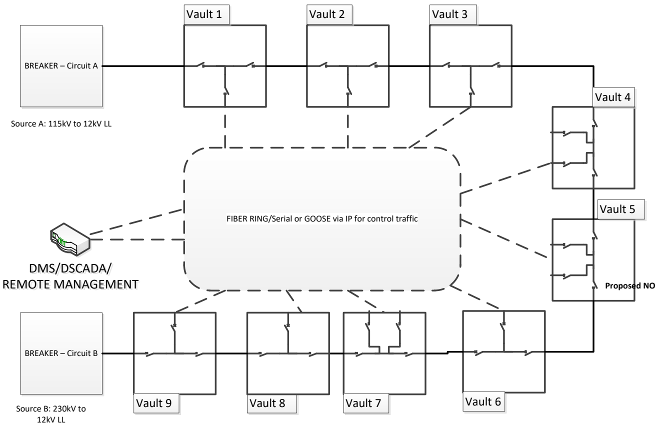

Figure 1: Layout of the automation system in Raleigh

As a design enhancement, the signals carried by each cable were apportioned such that two of the connectorized cables carry the binary and analog signals between the interface cabinet and the relay cabinet: one for the primary ways and one for the tapped way(s). This is integral to testing the system, as it allows the switch status, current and voltage signals to be disconnected from the physical switch and tested via simulation. This scheme is similar to that employed when testing reclosers; that is, the switch can be isolated and the control tested without operating the switch. For the purposes of this proof of concept, the configuration also allowed the control system to be tested without the switches (during the factory acceptance and final system acceptance tests). In future testing, it will allow for both individual relay testing and full system testing to be performed after the controls are installed without interrupting customer power.

A control pendant was also designed to connect to the interface cabinet. This pendant is attached by a 50-foot cable and allows the technician to monitor the switch status, operate switch ways and modify the relay modes while outside the vault. Additional cabinet connections include: battery backup, GPS time source and communications equipment (see Figure 2.)

For the telecommunications design, Duke Energy utilized a fiber gigabit ring network with two industrial switches at each vault node. A substation class grid router is utilized to route traffic on and off the ring to Duke Energy control and monitoring networks. Duke Energy designed the proof of concept telecom network to the same network design standard as is utilized for substation design allowing for off the shelf components to be utilized. A separate telecom cabinet was incorporated to allow maintenance access to the telecom equipment and to separate the telecom system from the control system. Two industrial switches are utilized at each node to allow for redundancy in the telecom system. Also, each relay was specified to have two physical Ethernet ports, with each port configured for failover capability, connected to a separate telecom switch at the node. This also provided another level of resiliency to the overall telecommunications assisted automation scheme.

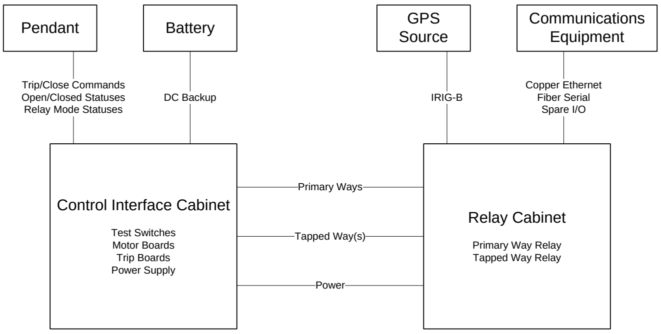

Figure 2: Control Block Diagram

III. AUTOMATION DESIGN

Each switch control system contains two IEEE Type 11 multifunction type relays for protection, automation and control. One relay is designated for the primary ways and the other for the tapped way(s). The tapped way relay provides overcurrent protection for the tapped ways in addition to control of the tapped way motors and fault interrupters. It also forwards serial based communication from the adjacent vault to the primary way relay. The primary way relay is responsible for loop protection and automation as well as control of the primary way motors and fault interrupters.

The automation system is designed in a modular fashion to allow for varying numbers of vault switches in a loop. The primary way relay communicates directly with the primary way relays in the adjacent vault(s), though some automation mode signals are communicated to all members of the loop. This design allows the settings in each relay to be virtually identical (except for the vault specific identifiers, communication parameters, etc.).

Two communication methods were used for the project: serial based and IEC 61850 GOOSE. These two protocols work in parallel for fault interruption and isolation; however, advanced automation features are implemented only in GOOSE messaging due to the additional signal points needed. The instantiation of a specific loop is accomplished by communication engineering. For serial based control, the port of one relay must be connected to the correct port of the remote relay. For GOOSE messaging, each relay must subscribe to the signals multicast by the remote relay(s). This hybrid communication design allows both for flexibility in communication installation (one or both protocols may be employed), for resiliency during faults (no single point of communication failure) and for the newer GOOSE messaging technology to be implemented while using serial based control as a backup (valuable for a company adopting new technologies).

One element specifically designed into the telecommunications system was the ability to segment GOOSE traffic into a separate communications layer than the telnet engineering and DSCADA control traffic. The purpose of this design was to contain the GOOSE traffic to the gigabit fiber ring due to GOOSE being a Layer 2 non-routable broadcast protocol. The grid router that connects to the fiber ring to allow DSCADA and engineering traffic to route to and from the ring blocks the GOOSE communications layer to prevent the broadcast traffic at the router. The GOOSE broadcast traffic can continue to navigate the gigabit ring independent of the operation of the network router for device to device communication within the automation system.

The automation system was designed to be rolled out in stages as construction progressed. Construction settings were used first and include local control, remote control and tap way protection only. After all vault switches and telecommunication equipment were installed, the relays settings group could be changed to a settings group that includes source transfer automation. This group includes the protection and control from the construction settings, but adds the ability to isolate a lost source at the head end of the loop and back feed from the alternate source. Once all switches, controls, communications and IEC 61850 engineering was completed and installed, the relay’s settings group could then be changed to include full automation. This settings group adds communication-coordinated fault interruption at the faulted section, isolation of the faulted section and restoration of customers on unaffected sections.

The following discussion describes the techniques used to locate the faulted section, isolate it and restore service to customers. Permissive Overreaching Transfer Trip (POTT) and Directional Comparison Blocking (DCB) have long been used in transmission systems to securely identify faulted lines [Elmore]. More recently these technologies have been brought to the distribution level thanks to cheaper and more flexible communications technologies. It has become more economical for a utility or campus to install fiber optic cable along with new underground cable. This fiber optic backbone can be used for Ethernet and serial communication by intelligent devices on the loop; networking the devices in the loop with each other and the substation. Once networked, these devices can communicate to one another via GOOSE messaging, to SCADA via DNP/IP and to the engineer via FTP or Telnet.

DCB is a communication based protection scheme that provides high-speed tripping for faults. DCB is an effective solution where traditional step-distance protection may not provide proper coordination. In a directional comparison blocking scheme a relay sends a blocking signal to an upstream relay if it detects a fault in the forward direction, indicating that the fault is outside of the upstream relay’s protected zone. The logic is programmed in each relay such that it trips when it sees a fault in the forward direction and does not receive a blocking signal from its downstream peer (see Figure 3.**Error! Reference source not found.**) The upstream relay will then send a transfer trip signal to its adjacent downstream peer to trip and isolate the faulted section. Once the switch on the opposite end of the faulted line is open it will send a close command in the opposite direction of the faulted line (downstream). This close command will be passed from relay to relay until it reaches an open switch. This switch will then close if it has a live alternate source. POTT is another communication based protection scheme that provides high-speed tripping for faults when step distance is not effective and when a line fault may be fed from both ends. In a POTT scheme, a relay sends a permissive keying signal if it sees a fault in the forward direction (towards the line). The remote relay will also send a permissive keying signal if it sees fault in the forward direction (see **Error! Reference source not found.**) If a relay receives a permissive keying signal from the remote end of the line and sees a fault in the forward direction it determines the fault is in its zone of protection and will trip. It will then send a transfer trip to the opposite end of the line. After both sides trip the fault will be isolated. Since the loop was initially closed, no further action is needed to restore power to customers. The POTT scheme requires information from the other end of the line and will only work when the remote relay is in service and the communication network between them is available. In case the communication network or remote relay is out of service, it is backed up by the DCB scheme described above.

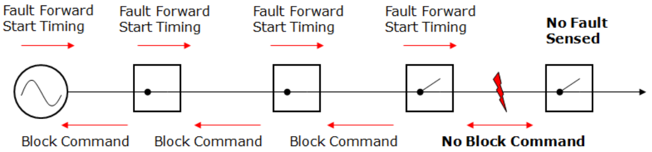

Figure 3: Direction Comparison Blocking (DCB) Scheme

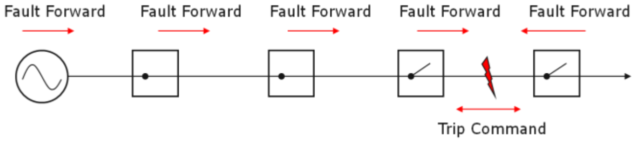

Figure 4: Permissive Overreaching Transfer Trip (POTT) Scheme

Restoration for external faults employs the source transfer scheme. The loop will normally have only one open point and the two switches closest to the upstream breaker will be designated as head end switches. These switches will use loss of voltage logic to detect when one or more phases of voltage is below the undervoltage set point for a given time without through fault current. Once the head end switch detects this condition, it will assume the upstream source to be lost or an upstream line to be faulted. The head end switch will open to isolate the presumed fault or lost source. Once opened, it will send a transfer close signal downstream. Similar to the fault isolation scenarios above, the close signal will be passed from relay to relay until it reaches an open switch. If the open point has an alternate voltage available it will close to feed the loop. After this reconfiguration the entire loop will be fed from the live source.

To support operator safety, the relay logic was designed to be placed in Remote Blocked Mode preventing all automation and supervisory control of the switches (including protection). If a switch is placed in Remote Blocked Mode and then experiences a fault, the fault will be cleared by the adjacent switches (upstream via DCB in the case of open loop, both sides via POTT in the case of closed loop). The only operations allowed in this state are manual operations from the pendant or relay.

Factory Acceptance Testing (FAT) tested all control hardware, relay logic and proved that the communication methodology was feasible and worked with temporary connections made at the vendor factory. During Site Acceptance Testing (SAT), it was necessary to retest not only the controls and logic, but also the communications system as built in the actual system. The ability to test the protection, automation, control and communication systems while the switches were disconnected from the relays was extremely valuable as it allowed the Duke to serve its customers during the SAT without requiring an outage. Due to project requirements, the switchgear had been previously installed, tested and energized.

While the core automation logic was the same between the FAT and SAT, the communications hardware and configurations as well as the IEC 61850 engineering had been changed from the FAT. It was therefore necessary to test all of these components as an installed system onsite. Having the controls separated from the switch allowed for fully testing all communications systems without impacting the customers. During the course of commissioning, communication was verified from the Relay Cabinet to the Communications Equipment within a single vault. After this was verified, communications between the vaults was confirmed; both the serial based peer-to-peer communication and the IEC 61850 communication and their configurations were tested. Testing included both checking for self-reported good communication as well as verifying the proper information was transmitted through these links during system testing.

IV. EQUIPMENT INSTALLATION

Due to physical limitations of vaults related to installation of switchgear coupled with the desire to eliminate excessive cable splicing and other undesirable configurations, there were some changes to the topology of the loop between the FAT effort and the final system build used for SAT. The primary way switches were either Switch 1 or 2 on every piece of switchgear but the direction of these switches with respect to the direction of power flow around the loop was reversed in some cases. When considering power flow around the loop from Source A to Source B, all the switchgear were oriented for power to flow into Switch 1 and out of Switch 2 for the FAT. Considering the same direction of power flow, some of the switchgear were installed in a manner in which power flows into Switch 2 and out of Switch 1 for the SAT and final system build.

Electrically, these changes are not a problem as the switchgear bus effectively acts as a node, but they presented some challenges with respect to the IEC 61850 GOOSE and serial over fiber communications schemes. Virtual bits and serial bits had all been mapped with a fixed system direction in mind. For GOOSE messaging, some multicast virtual bits are subscribed by every relay in the loop but those responsible for communication based protection functions are subscribed based on adjacency in the loop. The factory acceptance testing GOOSE subscriptions were based on the assumption that, going one direction, a Switch 1 would always be adjacent to a Switch 2. With the reversal of direction as it pertains to the primary way switches in some vaults, situations where Switch 1 is adjacent to Switch 1 in a neighboring vault and those where Switch 2 is adjacent to Switch 2 in a neighboring vault were introduced (see Figure 5**Error! Reference source not found.** & 6.) Challenges presented by this equipment installation change are discussed further in the Lessons Learned section of this paper.

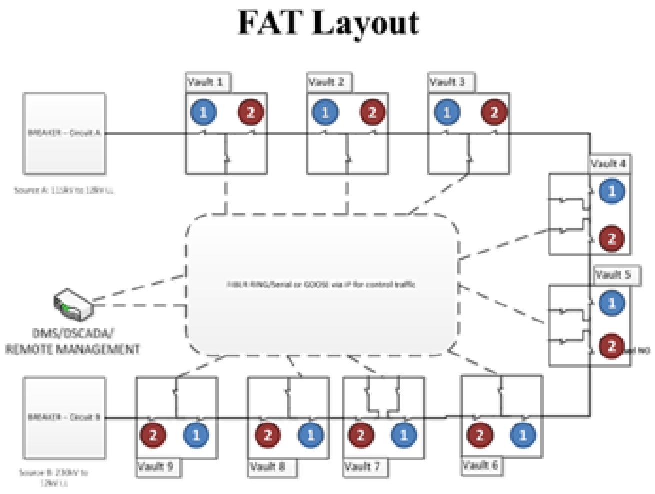

Figure 5: FAT System Layout

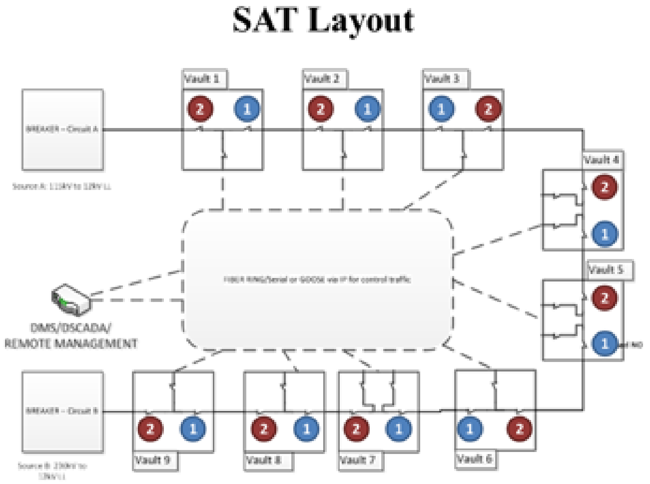

Figure 6: SAT System Layout

V. TESTING METHODOLOGY

Conventional testing methods require an end-to-end type test, where steady-state sequences for each test case and test set must be calculated. Then a technician or engineer would be required to input each test sequence in his or her computer, for each test location. Via a conference call testers would coordinate the next pulse from a GPS clock at which time all the test sets would synchronously inject the previously calculated and entered test sequence values. Upon successfully executing the test, all the results are then collected and analyzed to determine an assessment of whether each test case was successful or not. As the scope of this project was quite large and complex, this traditional method of testing was not ideal or practical.

To make the whole test setup operable, a novel software was used that had two key features: running a power system simulation and controlling multiple test sets from just one software instance. While using a power system simulation to calculate currents and voltages sounds like a complex solution, it makes the whole test case setup much easier. Only very few parameters are required to setup the power system model. After it has been entered, test case definitions are almost effortless. A fault on a line for example, must be dropped on to the location in the single-line diagram. The simulation takes care to calculate all currents and voltages correctly for each relay in the power system. Due to the feature of controlling multiple test sets from one instance, the test case can be started with just one button click. The software calculates the transient signals, distributes them to each test set and sets the start time. After execution, all binary traces measured at the relay are transferred back to the software, so they can instantly be assessed. Another important requirement to test the system was a circuit breaker simulation, which ran independently on the test set.

An example of a cable fault shall show how this system based test approach was used. First, a fault is placed on a cable. It is expected that the breakers feeding the cable isolate the fault. After successful isolation, the normally open breaker closes in and restores the supply. As the power system was already entered, the only thing necessary to define this test case was to place the fault on the cable segment (Figure7.)

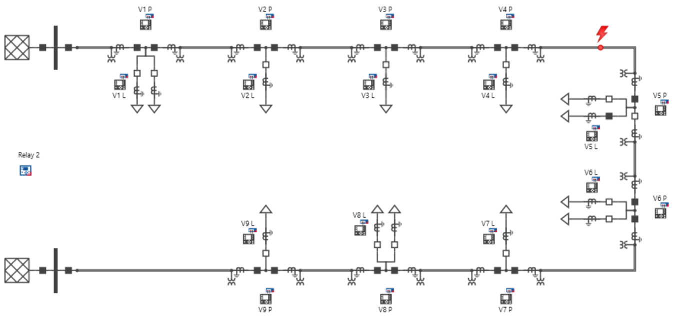

Figure 7: First event: fault active

The first execution injected a transient signal containing the fault incident. As expected the two breakers tripped selectively with a short delay. However, because the transient signals were already sent to all nine test sets, the test setup could not respond in real time. If the relays trip at the same time again when injecting the same fault quantities, the software automatically starts another iteration that will include the subsequent breaker events (Figure 8).

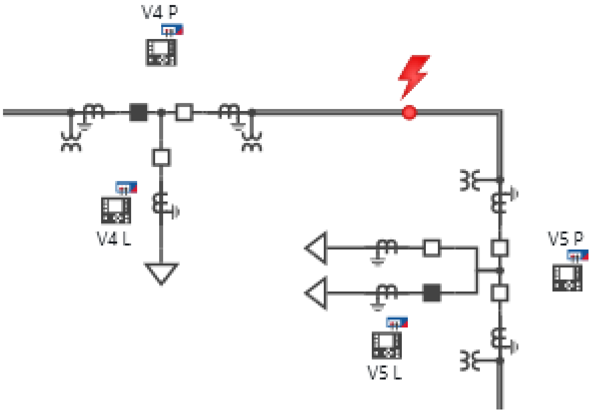

Figure 8: Second & third event: isolation

The same iterative process occurred again during the restoration. The test sets measured a close command for the normally open breaker. The software recalculated the transients now containing the fault event, the isolation events and the restoration event (Figure 9). With the last execution, we achieved a result similar to a real-time simulator.

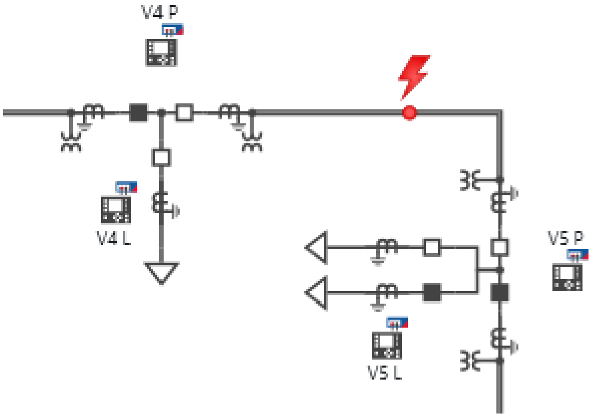

Figure 9: Fourth event: restoration

The advantages of this iterative closed-loop simulation are very simple test case definition and a better chance of finding error in the logic of the protection system. The test case definition does not require any parameters of the sequence following the fault. In case of a logic error, the misoperation is directly visible in the single line diagram, without investigating trip and close commands of ten relays in a binary trace diagram.

The full loop system under test consisted of nine individual underground vaults located around downtown Raleigh. Each vault contained two relays. The primary relay measures two three-phase currents over conventional inductive current transformers. The two three-phase voltages are measured via voltage sensors outputting low level signals. These conditions required each test set to have at least six phase currents and six low level voltage outputs.

For injection into the tap relay a second test set is required. To completely connect to every relay, 18 test sets would have been required. Duke Energy decided that, like the FAT, setting up an additional test set to each tap relay would be gratuitous. Duke Energy was interested to see the system behavior under full communication load, which primarily involves the primary relays. Each tap way could be tested in the loop scheme, separate from the other tap ways, while still allowing for a true test of the system.

Each underground vault test setup included one test set, connected to a GPS antenna, synchronized to IEEE 1588 precision time protocol (PTP). An Ethernet connection was then used to communicate between test sets via Duke Energy's existing fiber network. Due to the nature of the Ethernet connection, appropriate unique IP addresses needed to be assigned and coordinated with Duke Energy's internal Information Technology group.


Figure 10: Test setup inside vault

Each test set needed to be connected to a relay inside the vault. In order to achieve this, a custom test cable was utilized that connected all required signals from the test set (switch status, CT secondaries, etc.) to the relay cabinet, effectively simulating the switchgear. The test cable utilized the same submersible connector and pin configuration as the cable that connects the interface cabinet to the relay cabinet. This ensured an additional level of confidence by proving the physical connections in the relay cabinet.

All test cases were run on a single PC from a centralized location, above an underground vault located directly outside of the Duke Energy headquarters. This location was isolated from all public access via a secured gate, which allowed for the testing equipment to be setup on the ground level, instead of underground within the vault.

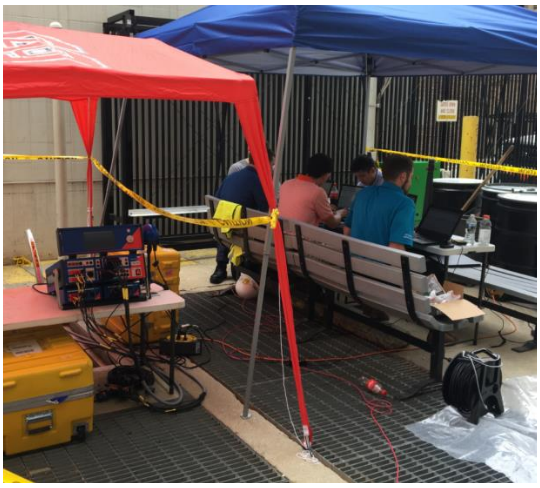
Figure 8: Location from which all tests were run

Two different groups of tests were performed to run the selected test cases proposed by Duke Energy. First, a series of half loop tests were performed, utilizing five different test sets, at four of the underground vault. Each vault location had its assigned GPS clock for synchronization, with one location containing two test sets and sharing a single GPS clock. The two test sets were located at the location which the tap way test would take place. This allowed for tests to be performed on eight of the primary ways and two of the tap ways. The second group of tests (full loop tests) included all nine vaults in the system, utilized nine test sets and focused on testing all 18 primary ways together as a system.

The test cases used for the site acceptance testing were based on the same list of cases used for the factory acceptance test but some changes were made. One use case that was developed following the FAT involved a real world, multiple section fault scenario that may potentially occur due to cable topology and portions of the network sharing a similar path. The vaults are not in a perfect horseshoe shape as shown in the configuration figures in this paper. There are a few locations where the lines between vaults that are not adjacent on the loop share the same path. It was determined that a potential use case in which a dig in or some other disruption could cause simultaneous faults on line segments between non-adjacent vaults may be possible. This use case was tested to ensure the system would respond in an acceptable manner.

VI. Lessons Learned

A. Planning Process

Multiple groups within each company (Duke Energy, G&W and OMICRON) worked together across several countries and time zones. This increased the level of planning and coordinating necessary to ensure everyone involved understood their roles and was able to contribute to the testing plans. The groups also needed to remain flexible as installation progress occasionally required some changes in plans. Personnel and test set availability as well a natural disaster (Hurricane Irma) required tight scheduling or rescheduling of the testing.

The team deemed it crucial to schedule periodic discussions of the current project status and to address team members' concerns. This framework allowed for a regular cadence of identifying issues as a team, performing individual research, and then discussing findings during subsequent team discussions.

B. Lessons learned to make setup smoother

The complexity of the system required that the design team coordinate up to nine test sets simultaneously. This setup demanded significant resources in coordinating all the test equipment to be on site for the test, as well as the personnel to set up all of the testing equipment in the individual vaults. Each test set required multiple connections for the analog and binary signals for injection and inputs from the relays, as well as connections for the GPS clocks. A simple connection error could result in the test providing incorrect results, and may require someone to physically go to the vault and correct the connection. The team found it very important to ensure that all test connections are verified prior to the start of testing.

C. Lessons learned from changes in FAT toplogy to SAT topology

Due to differences between the initial system design and the final system build discussed in the Equipment Installation section of this paper, changes were required to the IEC 61850 GOOSE virtual bit mapping and serial bit mapping. Relay logic also had to be updated to reflect these changes. These late stage changes presented a level of uncertainty for the site acceptance testing which proved to be warranted as discrepancies were discovered that required on-the-fly settings adjustments during the testing process. This change in system topology and the subsequent settings and communication changes have prompted a review of this method of design for systems of this nature. For future systems the communications aided tripping, virtual bit subscriptions, and serial bit mapping will all be done in a manner that is agnostic of switchgear installation. If this design methodology is not possible, there will be more effort early in the design process to better understand any site specific physical limitations so the design is more suited to the final build.

When designing the topology to be tested during the FAT it would have been beneficial not to assume that all switchgear would be oriented the same way with respect to the source breakers. If one or two devices had been intentionally reoriented in the FAT topology, the team would have learned more about the effects this has on the logic. Necessary logic changes could have been identified and implemented at the factory rather than during the SAT.

D. Location challenges

Figure 12: GPS Strapped to the top of the vault for increased signal strength

Due to heavy foot traffic around each of the underground vault locations, the design team determined that it would be best to locate associated testing equipment within each of the nine vaults, to avoid having the equipment located on the ground level, and having dedicated personnel monitoring each exposed access point. With the GPS clocks located in an underground vault, they did not have direct line of sight to open sky, which resulted in some loss of communication failure during the test set up. This challenge was overcome by locating the GPS clocks as close as possible to the ground level to allow for uninterrupted communication.

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