SITE ACCEPTANCE TESTING OF A DUKE ENERGY DISTRIBUTION 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.

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 the switches. This paper discusses the overall requirements and design of the protection system and its related hardware, 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.

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.

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 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 voltage (transmission) sources was rated at 115kV line to line and the other high voltage (transmission) source was rated at 230kV line to line.

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. 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. The factory testing was the subject of a previous paper [Keller et al.].

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. 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.

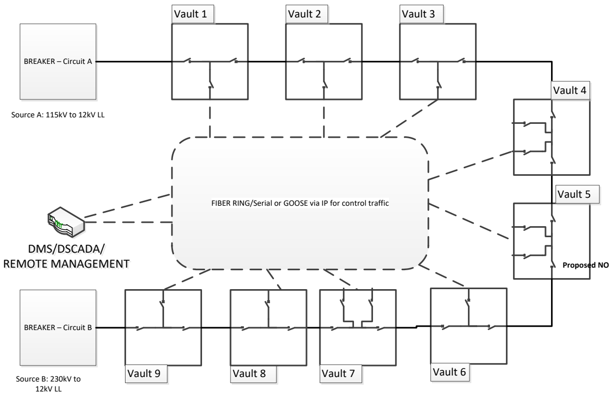

Figure 1: Layout of the automation system in Raleigh

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, 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 between vaults and one for the tapped way(s) for the load. This is integral to testing the control system. Using two cables to carry the signals allow the switch status, current and voltage signals to be disconnected from the physical switch and tested via simulation 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's control and monitoring networks. 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.

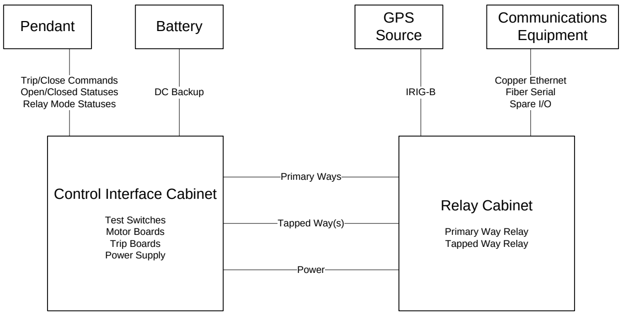

Figure 2: Control block diagram

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.

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 and 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 grid router 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 grid 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. Once all switches, controls, communications and IEC 61850 engineering were 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.

Two techniques are used to interrupt and isolate the faulted section and then restore service to customers: Directional Comparison Blocking (DCB) and Permissive Overreaching Transfer Trip (POTT). Both DCB and POTT are communication based protection schemes that provide high-speed tripping for faults. They are both effective solutions when traditional step distance protection may not provide proper coordination, with POTT being used when a line fault may be fed from both ends of the loop. The POTT scheme only works when the remote relay (downstream from fault location) is in service and the communication network is available. In case the communication network or remote relay is out of service, it is backed up by the DCB scheme.

Restoration for external faults employs the source transfer scheme. The loop will normally have only one open point. The two switches closest to the upstream breaker (head end switches) use loss of voltage logic to detect and isolate an external fault or lost source. Once open, the head end switch sends a transfer close signal downstream to the normally open switch. If the open point has an alternate voltage available, it will close to feed the loop.

EQUIPMENT INSTALLATION

Due to physical limitations of vaults related to installation of switchgear, 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 switchgears 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 such a way that 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 of GOOSE subscriptions assumed 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 3).

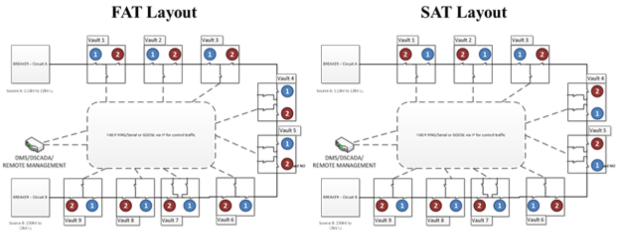

Figure 3: System layout FAT vs SAT

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 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 of calculating 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 (Figure 4).

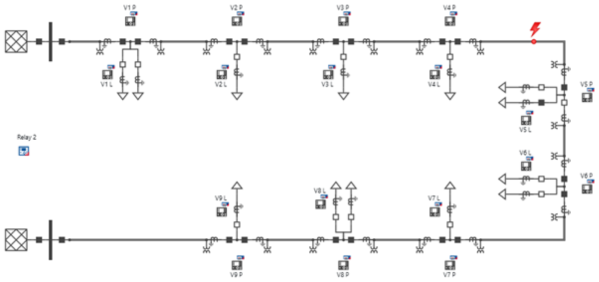

Figure 4: First event: fault active

The first execution of the test case 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 5).

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 6). With the last execution, we achieved a result similar to a real-time simulator.

The advantages of this iterative closed-loop simulation are very simple test case definition and a better chance of finding errors 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 miss operation is directly visible in the single line diagram, without investigating trip and close commands of ten relays in a binary trace diagram.

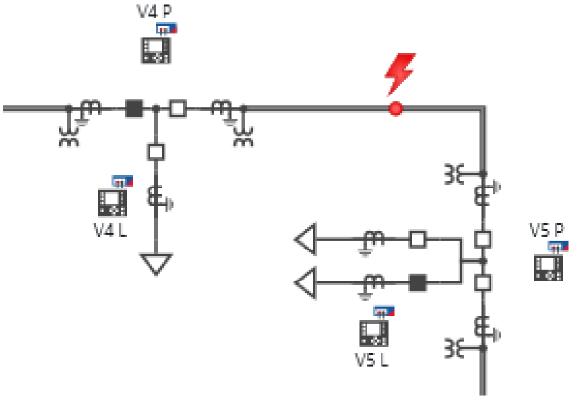

Figure 5: Second and third event: isolation

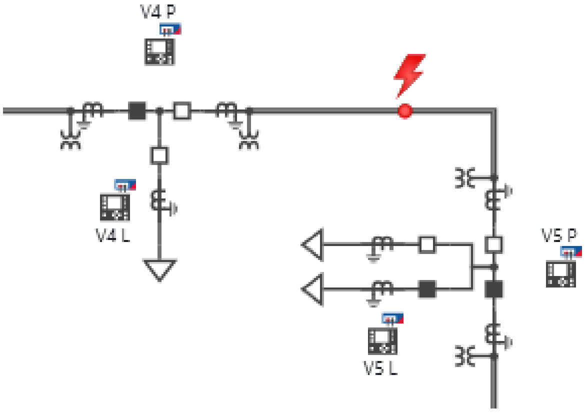

Figure 6: Fourth event: restoration

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 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. 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 used to communicate between test sets via Duke Energy's existing fiber network. A custom test cable was utilized to connect all the required signals from the test set to the relay cabinet, effectively simulating the switchgear.

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. 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 vaults. 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.

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.

LESSONS LEARNED FROM SITE TESTING

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.

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 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.

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.

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.

REFERENCES

[1] E. Keller, P. Hoffman and C. Pritchard, 2016, "Factory acceptance testing of a Duke Energy distribution automation project utilizing a simulation based test approach", *Proceedings 43rd Annual Western Protective Relay Conference*