Smart Grid – Smarter Protection: Lessons Learned

Kevin Damron and Randy Spacek
Avista Utilities

Abstract — Avista embarked on a ‘smart grid’ initiative through grants provided by the Department of Energy (DOE) and the American Recovery & Reinvestment Act in 2010. Along the way many lessons were learned from the concept phase to the implementation phase of a 13.8kV distribution ‘smart grid’ system. At times, the behavior of the distribution system did not respond as expected or original assumptions were incorrect. The paper will discuss the challenges and solutions devised by the System Protection group for the deployment and integration of intelligent devices performing protection and control on the Avista 13.8 kV distribution system. Topics of discussion will center on:

- Back-to-back midline recloser coordination
- Fault identification and status integration to Distribution Management System/Operations
- Forward and reverse element directional security
- Recloser/Switch Functionality
- Automatic reclosing and stall logic
- Harmonic element blocking
- High-set instantaneous overcurrent elements

Several system events will be discussed and analyzed to describe when the system worked correctly and when the response was not as expected. The solutions developed to mitigate the problem with the response will be presented for the unexpected operations. The paper also addresses lessons learned and provides suggestions for other utilities considering a similar design.

I. BACKGROUND & INTRODUCTION

Communication and automation are key elements in updating the aging grid to support the new technologies of today and tomorrow. Ultimately, the work will result in greater energy efficiency for energy delivery, slowing the need for new large central generation facilities and easily allowing the integration of distributed energy resources.

Avista’s Smart Circuits project upgraded electric facilities in the Spokane and Pullman areas with the help of federal stimulus funding. In 2010, the U.S. Department of Energy awarded Avista two grants, $20 and $13 million in investment grant funds, the largest matching smart grid investment grant in Washington. Avista contributed $22 and $26 million for a total project investment of $42 and $39 million respectively. The two grants were; the Smart Grid Investment Grant Project for the installation of intelligent field devices, communication connectivity and software systems enabling a Smart Grid; and the Smart Grid Regional Demonstration Project for the development of interoperability architecture to demonstrate the benefits of deploying Smart Grid technology as a region.

The funding allowed Avista to accelerate the pace of upgrades planned for the distribution system. Over a two-year period Avista deployed a distribution management system (DMS), intelligent end devices, communications systems, and integrated substations benefitting more than 110,000 electric customers in the Spokane and Pullman regions. The projects were intended to reduce energy losses and improve efficiency by active management of the distribution system through the control of intelligent devices and improve reliability through monitoring the distribution system and performing fault isolation automatic restoration. The project involved upgrading 71 distribution circuits and 17 substations throughout the Spokane and Pullman areas. The upgrades included installation of ‘smart’ switches, midline reclosers and ‘smart’ capacitor banks on feeders plus the installation of substation relays and regulator controls.

Figure 1 shows the reduction in sustained outages related to grid modernization.

II. BACK-TO-BACK MIDLINE RECLOSERS COORDINATION

Avista employs a 500 Ampere feeder and a half scheme where one feeder is capable of serving half the load of an adjacent feeder. Prior to the smart grid initiative, Avista had primarily older midline reclosers on the distribution system providing no operational data or control. A typical recloser installation would be based on the relay reach for fault detection, separation of a heavily loaded feeder or to isolate laterals or
trouble areas. All back to back feeder ties were through manual switches.

The installation and integration of ‘smart’ reclosers and switches provides operational data and control via communications with the protective relays. Several technologies were used for the communications including cellular radio and wireless mesh networks based on the specific area. The smart grid initiative also provided the opportunity to upgrade the communications infrastructure in the associated substations. The substation protective relays were upgraded if necessary for the smart grid feeder. Figure 2 shows an example smart grid feeder circuit.

The topology shown in Figure 2 leads to several ‘game changers’ for the traditional protection schemes Avista had used for years on the distribution system. The new topology divided the feeder main trunk into 125 Ampere sections based on peak load with an intelligent device between each section. In addition each section had a tie to an adjacent feeder through an intelligent device. The location selection for the midline recloser was typically two sections out on the feeder with a switch between the substation and the midline recloser. The fault duty and separation by distance were not considered. The first game changer was the Distribution Management System (DMS), during restoration any number of sections could be picked up from an adjacent feeder based on the previous/predicted loading and system capacity with no verification of protection settings or coordination. Secondly, the DMS switching created a need for reverse protection sensitivity under alternate system configurations with multiple intelligent devices in series. The number of coordination challenges lead to a need to ‘out smart the smart-grid’.

If the normally open (N.O.) Tie 1 switch shown in Figure 2 is closed and the Sub R feeder breaker is open, then the distribution system fault current magnitudes diminish for an end of line fault. In addition the previous load of the feeder has doubled. An example case is maintenance on the feeder distribution system fault current magnitudes diminish for an end of line fault. Avista’s DMS uses the lockout of a feeder breaker or midline recloser to initiate fault detection, isolation, and restoration (FDIR) logic. However, the DMS did not receive a lockout notification for the permanent fault. When the recloser was closed via DMS, the lockout target appeared after closing. The protection system had operated correctly for the fault, but FDIR failed to initiate resulting in customers experiencing longer outages. Figure 4 shows the logic in the midline recloser when the lockout to DMS failure occurred.

Subsequent analysis determined the timing of when the recloser entered the lockout state (79 Lockout) as the reason the lockout targets failed to assert thus causing FDIR to not initiate. The timing is affected by the breaker auxiliary contacts (52a) which opened much slower than the breaker contacts for the event. The 79 Lockout logic is internal to the relay and cannot be altered. The recloser manufacturer was contacted and the breaker contact status variability was confirmed. The variability and the drop-out of the overcurrent supervision resulted in lack of lockout indication to DMS.

When the recloser was subsequently manually closed, the conditions in Figure 4 were met due to inrush/cold load pickup current and resulted in a lockout indication to DMS.

Figure 5 shows the modified logic implemented to fix the lockout indication to FDIR by removing the variability of the breaker contact (52a). The Trip Three Pole is extended by the supervising voltage ensures the feeder is healthy and a controlled sequence is attained. The coordination problem is solved by using the directionality of the protective relaying and the relay logic. Figure 3 shows the completed sequence of operations for fault (where T = trip, R = reclose, and LO = lockout). The design removes any requirements for communications between the reclosers.

III. FAULT IDENTIFICATION TO DISTRIBUTION MANAGEMENT SYSTEM (DMS)

During the winter of 2014, a smart grid feeder faulted downstream of a midline recloser. The permanent fault resulted in the midline recloser going through a trip/reclose cycle to lockout. Avista’s DMS uses the lockout of a feeder breaker or midline recloser to initiate fault detection, isolation, and restoration (FDIR) logic. However, the DMS did not receive a lockout notification for the permanent fault. When the recloser was closed via DMS, the lockout target appeared after closing. The protection system had operated correctly for the fault, but FDIR failed to initiate resulting in customers experiencing longer outages. Figure 4 shows the logic in the midline recloser when the lockout to DMS failure occurred.

Subsequent analysis determined the timing of when the recloser entered the lockout state (79 Lockout) as the reason the lockout targets failed to assert thus causing FDIR to not initiate. The timing is affected by the breaker auxiliary contacts (52a) which opened much slower than the breaker contacts for the event. The 79 Lockout logic is internal to the relay and cannot be altered. The recloser manufacturer was contacted and the breaker contact status variability was confirmed. The variability and the drop-out of the overcurrent supervision resulted in lack of lockout indication to DMS.

When the recloser was subsequently manually closed, the conditions in Figure 4 were met due to inrush/cold load pickup current and resulted in a lockout indication to DMS.

Figure 5 shows the modified logic implemented to fix the lockout indication to FDIR by removing the variability of the breaker contact (52a). The Trip Three Pole is extended by the
trip duration even though the breaker has changed state and the over current elements have dropped out.

IV. FORWARD & REVERSE DIRECTIONAL ELEMENT SECURITY

One of the challenges experienced with using the forward and reverse logic in the protective relays was the functionality of directional elements on a distribution system. Figure 6 shows the event report for a midline recloser on a radial 13.8kV distribution feeder during a B-C fault.

At the beginning of the fault, the reverse directional control (32PR) of the phase overcurrent elements asserted unexpectedly resulting in the reclosing driving to lockout after only one reclose attempt. Several factors of the distribution feeder affect the directionality logic which includes a standing imbalance resulting in negative-sequence current (3I2) and the VAR flow on the distribution system. Due to the conditions of negative sequence and the current leading the voltage the calculated negative sequence impedance directional element was reverse. The reclose logic requires the upstream voltage present, the load (voltage) is de-energized and the forward fault latch present for reclosing to occur. Since the reverse fault latch was set instead of the forward fault latch, the recloser did not complete the reclosing cycle and locked-out before a downstream fuse could clear.

Avista’s solution was to delay the directional decision until 1-cycle into the fault based on the rising edge of the trip signal (TRIP3P). The delay allows the reverse signal to drop-out prior to the relay setting the directional latch used in the reclosing logic.

V. AUTOMATIC RECLOSE & STALL LOGIC

In 2012, a fault occurred on a 13.8kV distribution lateral protected by a 40T fuse shown in Figure 7 while a crew was working on the feeder between the substation and the midline recloser.

The crew had taken a hot-line hold (43H/HLH) on the feeder as part of the work. Avista uses the HLH to enable instantaneous tripping and to block reclosing during energized work. A temporary fault occurred on the 40T lateral causing the midline recloser and feeder breaker DAL 131 to trip. The crew subsequently went to the substation, cleared the HLH, and closed DAL 131 and believed they had restored all service to customers on the feeder. However, customer calls due to outages downstream of the midline recloser later were received. The installation of new midline reclosers using micro-processor relays have changed Avista’s old practice of using Kyle, Basler, and electro-mechanical relayed reclosers. The new micro-processor relays caused confusion for the crews as they operate differently. For the DAL 131 lateral fault, the recloser locked-out prior to reclosing when the DAL 131 feeder breaker was closed. The pre-existing Kyle recloser had been replaced as part of the feeder upgrade the prior year. The crew expected the micro-processor relay recloser to operate identical to the Kyle recloser by ‘stalling’ during the reclosing cycle if the upstream/source-side voltage was lost and would complete the reclose when the upstream/source-side voltage returned. Avista’s distribution operations engineers asked for the review of the operation since the midline recloser was located ~30 miles away on the other side of a lake from the substation and there was confusion about the operation. A review of the midline recloser logic found upon the open interval time out, the recloser checks the reclose supervision logic and will ‘wait’ for the logic to be satisfied for 5 seconds (user settable) and then would drive to lockout. The reclose supervision logic included a “hot-bus/dead line” element for forward faults and “hot-line/dead bus” element for reverse faults in the logic. The micro-processor relay used in the midline recloser included user settable ‘stall logic’. Avista chose to use the logic to ‘stall’ the reclosing logic until three-phase voltage was available to the recloser which emulates the electro-mechanical relayed reclosers.

For the previous scenario with the new ‘stall logic’, the midline recloser would have ‘stalled’ since the DAL 131 feeder breaker locked-out. When DAL131 was closed, the midline would have completed the reclose once it sensed...
three-phase voltage thus restoring service to all customers with the exception of customers on the 40T fuse lateral. The logic is implemented on all laterals where no tie exists.

VI. RECLOSER/SWITCH FUNCTIONALITY

Figure 8a shows a portion of Avista’s smart grid distribution system in the normal configuration with two feeders being supplied from the substation. Midline reclosers are noted by the ‘R’ in the square box and the other boxes are switches. The forward direction of the midline reclosers is also shown in Figure 8a. The two feeders can be connected through a normally open (N.O.) switch. Avista chose to install relayed reclosers as switches in much of the smart grid system for both flexibility and reduced costs. The switches only protective functions are instantaneous (50P/50G) overcurrent elements enabled when a hot-line hold (HLH) is selected. Avista uses the HLH to enable instantaneous tripping during energized work. The switches are never set to fault interrupt or provide automatic reclosing or they would be designated as a recloser.

Midline recloser Z02R is special since it is a midline recloser in the normal system configuration (Figure 8a) and a switch in the alternate system configuration (Figure 8b). Midline recloser Z02R will only trip for forward faults by use of the directional element logic available in the micro-processor relay. When the system is configured in the alternate system configuration, the system is radial from the substation and faults downstream of Z02R (towards Z03R) are reverse to the Z02R midline recloser. The flexibility still allows for a non-directional HLH to be applied on Z02R allowing for a reduced area affected by HLH work. The change in the functionality of midline recloser Z02R is required to maintain coordination in the alternate system configuration due to short distances, high available fault duty, and number if intelligent devices in series.

VII. HARMONIC ELEMENT BLOCKING

During the winter of 2014, the WAL (non-Smart) Grid distribution feeder operated to lockout due to a tree in the distribution line. The crews patrolled the line and discovered a tree in the line and the decision was made to restore the majority of the customers by back-feeding the feeder from an adjacent substation via a normally open switch. When the switch was closed the LKY feeder breaker tripped and reclosed successfully but subjected the loads to a “blink”. The subsequent morning, System Protection received a phone call from the area engineer stating “you had a miscoordination since I was only picking up 40 amps of (13.8kV) load”. Figure 9 & 10 show the trip when the WAL feeder load was picked up from the LKY feeder.
The LKY feeder took approximately three-minutes for the load to return to normal. Avista typically sets the pickup of the overcurrent elements at twice the load to allow for cold load pick up. Reference [1] provides background on cold load pickup issues and possible mitigation methods. The microprocessor relay Avista uses does not have cold-load pickup logic but does have second-harmonic blocking logic. Figure 11 shows the harmonic content during the initial trip and the vendor second-harmonic blocking logic.

Subsequent testing proved delaying the phase and ground instantaneous elements using the vendor second-harmonic blocking logic prevented tripping and reclosing for cold load pickup without limiting the speed of protection for an actual fault since faults have low harmonic content. The logic has been added into the standard settings for future deployments after discussing the changes with Avista’s operations engineers.

VIII. HIGH-SET INSTANTANEOUS OVERCURRENT

Figure 12 shows an older (circa 1947) substation having five smart grid 13.8kV distribution feeders in the same right-of-way. To compound the issue, the available fault current at the substation is high. Prior to the smart grid initiative, all of the feeders were protected by electro-mechanical protective relays.

Avista had experienced an instance of two feeders short-circuiting at the structure shown in Figure 12 in the past. The fault resulted in the transformer protection operating as the fault current divided between the two feeders and resulted in slower operating times for the 13.8kV feeder breaker protective relays. The feeders are normally operated with instantaneous disabled so not to blink the entire feeder disrupting all customers. When the smart grid upgrade of the substation began, the distribution operations engineers asked if something could be done to mitigate the possibility of the scenario again.

The new micro-processor relays installed as part of the smart grid initiative offer multiple levels of overcurrent elements. Avista chose to use one level of phase and ground instantaneous overcurrent elements in the feeder breaker protective relays to provide protection for the 5-circuit structure. The high set instantaneous elements are set to 130% of the next downstream interrupting device. The high-set phase and ground instantaneous overcurrent elements are not disabled via the front-panel, reclose operation, or hot-line hold removal.

IX. MULTIPLE FEEDER FAULTS

Prior to the installation of breakers and reclosers with microprocessor relays, event records were not available for distribution faults. Like many other utilities, if an unexplained operation occurred on a feeder, Avista tested the protective relays and if they worked correctly just ‘moved on’. Though the event analysis has increased the post-event analysis has also given insight into more understanding of the distribution system. Figure 13 shows the BEA 12F5 13.8kV distribution feeder with a midline recloser and a 100T fuse on a lateral branch.
The following is a summary of the operations:

At 12:37:52
  • Mylar balloons got into a lateral with 100T fuses. The remains of balloons were found and two 100T fuses had blown.
  • BEA 12F5 and the midline recloser Z337R did not operate for the fault although they ‘saw’ the fault. Time overcurrent elements began to time, but the fault was cleared by the fuses after ~15 cycles.
  • The fault was an AB fault with approx. 2415 A of fault current.

At 12:37:55
  • A second AB fault (~6.5kA at roughly 0.42 miles from the substation) then occurred.
  • The feeder breaker BEA 12F5 tripped (via a high set instantaneous, 50P3)
  • The fault was upstream of the midline so it didn’t operate.

At 12:37:55.771
  • The feeder breaker BEA 12F5 reclosed for the 1st time after a 0.5 second time delay.

At 12:37:57
  • The feeder breaker BEA 12F5 tripped again as the fault reinitiated.

At 12:38:09
  • The feeder breaker BEA 12F5 tripped again and went to lockout (LO) as expected.
  • The fault was approx. 5.7kA, roughly 0.2 miles from the substation, and was a BC fault.

At 13:01:23
  • The midline Z337R was opened (DMS Operations received fault indication downstream of the midline).

At 13:02:24
  • The feeder breaker BEA 12F5 was closed and Z337R was closed.

Several similar faults have occurred on other Avista distribution feeders in which the downstream (of the midline recloser) fault resulted in an upstream fault occurring. The distribution line was patrolled and the ~6.5kA fault location was discovered based on the feeder protective relay fault location. Prior to having the midline recloser and the protective relay event information the operation would have likely been thought of as a misoperation/miscoordination. Having the event information allowed Avista to identify the 2nd fault location and discover a long-span of damaged distribution feeder.

X. CONCLUSION

Micro-processor protective relays offer many additional tools which can be used by the protection engineer in smart-grid applications. The tools are necessary to address many of the challenges introduced by the complexity of non-radial distributions systems and require the engineer to think differently about distribution systems.

This paper presents novel approaches to address the challenges that a smart-grid design introduced into Avista’s electrical distribution system.

XI. REFERENCES
XII. ACKNOWLEDGEMENTS

The authors wish to thankfully acknowledge their colleagues, Tim Figart, Jon Harms, and Mike Diedesch in Avista’s System Protection group (past and present) who contributed to the design and implementation of Avista’s smart grid.

XIII. BIOGRAPHIES

Kevin Damron received his BS in electrical engineering from the University of Kentucky in 2001 and a ‘Power Systems Protection and Relaying’ certificate from the University of Idaho in 2009. Upon graduating, he joined Schweitzer Engineering Laboratories, Inc. as a power engineer in the research and development division. Prior to joining Avista Utilities in 2010, he was employed by Eta Engineering Consultants (EEC), PSC providing engineering and consulting services. Kevin has broad experience in the field of power system operations, maintenance, and protection and has authored/coauthored several papers on protective relaying. Kevin is a registered professional engineer in Washington State, an adjunct professor at Gonzaga University, and is a member of IEEE.

Randy Spacek graduated old school with a BS in Electrical Engineering from the University of Idaho in 1985 with a power emphasis and claims to be a Professional Engineer. He has over 29 years experience in the electric utility industry as he has toured the Pacific Northwest in various positions. Presently he manages the System Protection group at Avista. Upon rejoining Avista in 2001, he has been unable to escape system protection and is being pigeon holed. He has too many accolades in his own mind to list here. Randy has provided training at the Hands on Relay School and presently chairs the WECC Relay Work Group.

© 2015 by Avista Corporation
All rights reserved.
20150914