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CIGRE US National Committee
2012 Grid of the Future Symposium

Case Study: Collaborative New Design, Engineering, and Testing Practices Provide Successful Adoption of IEC 61850

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SUMMARY

Replacing hard-wired connections with digital communications over Ethernet requires new engineering and testing practices. PPL Electric Utilities Corporation (PPL) recently designed, installed, and tested a new high-voltage substation using next generation relay and control equipment. This next generation substation (NGS) is based on networked Ethernet intelligent electronic devices (IEDs) communicating via IEC 61850. This paper discusses the new technical design details of networking IEDs over Ethernet, but more importantly, it also discusses how engineering, installation, and testing practices had to change to accommodate the new technology. PPL methodically replaced their previous protection and control design with a design that provides more functionality while migrating to IEC 61850 communications from multiple IED manufacturers.

In the end, over 50 percent of the hardware, 60 percent of the hard-wired connections, many disparate programmable devices, and several software programs were eliminated. New testing techniques were developed to test IEC 61850 communications, and wiring drawings were replaced with Generic Object-Oriented Substation Event (GOOSE) messaging tables so that test technicians could identify the endpoints of the virtual wires.

The NGS implementation required completely new communications design methods, IED configuration, verification testing, and system commissioning. This paper describes the PPL process of developing best engineering practices for substation protection, integration, control, monitoring, metering, and testing. A discussion of these engineering practices and how they evolved provides valuable insight to engineers considering using one or more of the IEC 61850 protocols for peer-to-peer protection and automation or client-server methods for integration and automation.

Lessons learned were associated not only with new technology but also with new procedures, such as how test technicians selectively block signals that communicate over Ethernet without physically disconnecting the IED from the network. This paper also discusses the PPL creation of a project team consisting of representatives from engineering, operations, standards, and relay testing to collectively resolve concerns associated with system testing, future expansion, and maintenance of the NGS design.

KEYWORDS

Engineering, operation, design, IEC 61850, substation.

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1 INTRODUCTION

Previous PPL Electric Utilities Corporation (PPL) substation integration and automation systems used redundant programmable logic controllers (PLCs) as the substation data concentrator. Substation information was collected by the substation PLCs using discrete I/O interface modules, interposing relays, and serial communications to intelligent electronic devices (IEDs) via direct connection. The substation PLCs would then pass this information to the supervisory control and data acquisition (SCADA) remote terminal unit (RTU) before the information was sent to the SCADA master.

Rather than propagate the existing PLC-based design, PPL engineers developed an alternative that incorporated the existing IEDs and improved the integration and automation, while also simplifying the system architecture. The new design relies on several protocols within IEC 61850 to support peer-to-peer relay communications, the human-machine interface (HMI), and SCADA connections. Fully utilizing the available I/O in the relays and other IEDs essentially replaces large amounts of copper contact and transducer wiring with a few communications cables. The result eliminates equipment and reduces configuration, installation, commissioning, and maintenance costs.

Although the new data acquisition methods promise to reduce the overall amount of manual labor, they also dramatically change the technology used for system configuration, installation, commissioning, and maintenance. These new technologies require new processes to provide an understanding of unseen data flow inside the communications network and a certainty that the protection and control systems will operate properly.

Compared with previous publications on the same topic, the new contribution of this paper is the discussion of the importance and use of real-time communications interface diagnostics through lessons learned during commissioning and maintenance activities.

2 CHANGES TO METHODOLOGY

One major difference that affects all parts of commissioning and testing is that the new PPL next generation substation (NGS) design uses a single Ethernet port on each IED. The second major difference is that all PLCs are eliminated, and the upper-tier PLC is replaced with a communications processor.

2.1 More Microprocessor-Based IED Multifunction Capabilities

Using functions already built into the microprocessor-based relay has eliminated the hardware and associated panel wiring of the previous PLC-based design. For example, the bay PLC and fault detector were eliminated by moving breaker failure and direct transfer trip (DTT) logic functions into the relay. Digital transducers were also removed because the necessary data were already available in the microprocessor-based relays. Because the analog data are now available through the Ethernet port, PPL uses relay data to support the SCADA system, without the need for additional transducers. Previous substation designs used microprocessor-based relays for protection only. Other functions, such as fault detection and Sequential Events Recorder (SER) reporting, were performed by dedicated devices. The flexibility and reliability of microprocessor-based relays allowed the elimination of dedicated devices from the NGS design, because these functions now reside in the relay.

2.2 Replacing Wired Terminations With Digital Communications

Protective relays now perform many functions besides protection. The advantages that modern microprocessor-based relays provide over traditional relays are well documented. These advantages include fault location, event reports, and programmable logic that allows many functions to be included in one device, thus saving hardware and wiring costs. One important complication of the technology shift is the increasing portion of the protection system design that resides in algorithms and logic in relays [1]. With the elimination of devices and hard-wired connections, new methods of testing and documentation had to be developed. Points previously hard-wired are now broadcast onto an Ethernet network via IEC 61850 Generic Object-Oriented Substation Event (GOOSE) messages.

2.3 Communications Messaging Isolation for Test

Procedural challenges must also be expected when a new design is developed. For instance, how do test technicians selectively block signals communicating over Ethernet? To address these and other important issues, a project team consisting of representatives from engineering, operations, standards, and electrical testing was formed. Issues were discussed at length, and the system was designed to accommodate concerns associated with testing, scaling and expanding, and maintaining the design. For example, with previous substation designs, the need to block a particular function was imposed by opening a physical switch in the relay contact wiring circuit. The NGS utilizes a logic qualifier in the relay to block or enable GOOSE message broadcasts.

Because all IED communications are now interleaved through a single Ethernet port, PPL devised a way to isolate individual communications paths. When an operator chooses to block a GOOSE message, the contents are not actually updated. Although the IED GOOSE messages continue to be published, the payload, or data set, will not be updated with new values when the message is blocked. The HMI test display was modified to include a control to enable and disable the GOOSE data set update. When the operator chooses to disable GOOSE updates, a logic bit is set in the HMI and sent to the IED. The IED constantly checks this logic and its status with the update process. Using this method, individual bits or entire data set contents can be blocked from being updated in outgoing IED GOOSE publications.

2.4 Communications Messaging Changes for HMI Update

With the elimination of PLCs and single-function devices, the substation network evolved to an Ethernet network, supporting multiple SCADA, peer-to-peer, and engineering access protocols. Manufacturer-provided software tools were used to develop relay logic, HMI programming, field simulation, testing, and documentation.

The changes to the HMI were kept to a minimum. This was done by simply changing the application that updated the HMI database from a SCADA protocol to IEC 61850 Manufacturing Message Specification (MMS). Using MMS, the database is now updated using a client-server protocol.

With the ability to communicate with each relay came the possibility for comparative logic in the HMI. When multiple relays provide data for one apparatus, such as a tie breaker, the HMI compares the data from all sources and flags any discrepancies. The HMI provides the operator with the ability to view all data sources via a health indicator button and determine which relay is not in agreement. This function is illustrated in Figure 1. The operator also has the capability to remove the questionable IED from the scan.

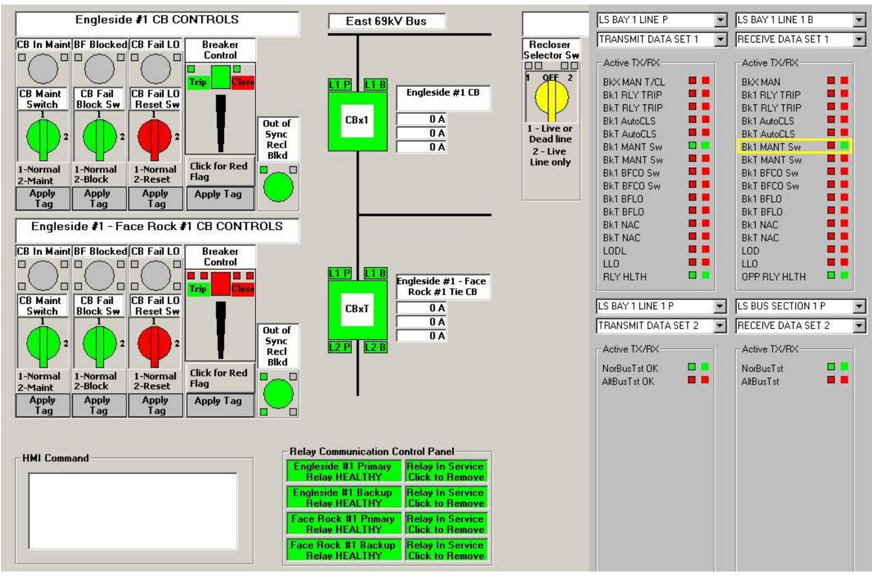

Figure 1 HMI display illustrating IED values, IED health, and GOOSE payload verification

The health and status of the relays are constantly monitored within the HMI to ensure accurate data are presented to the user. Because the protection design includes redundant relaying, any data disruption from a primary relay will cause the HMI to shift to the backup device for any analog data. Status data display is handled differently. In order to ensure the relays remain consistent, the statuses of all the devices are combined using a Boolean AND statement. Any discrepancies between status values in the relays will be indicated with a yellow flag on the affected device(s). The HMI one-line and device control screens indicate abnormal health or status with a red or yellow alert icon for each affected relay. The HMI also allows the user the option to force any relay out of service and disregard any data coming from that device. This is useful when removing a relay from service to perform testing or maintenance without affecting the HMI status and analog quantities.

2.5 Point Verification

PPL developed an HMI application that provides GOOSE monitoring to aid in verification of peer-to-peer digital communications interconnections. The application creates and displays GOOSE diagnostics as well as the data set contents from each IED. It also supports control of the GOOSE message behavior from the IEDs. Like the hard-wire tests before, GOOSE test methods support iterative tests during commissioning as well as future changes and additions. The test results are saved, and screen captures of the GOOSE monitor application are saved as test process artifacts.

The GOOSE system is designed around standard transmit data sets that serve two distinct purposes. The intent of the first transmit data set is to exchange protection data and ensure consistency between the redundant relaying data. Other transmit data sets serve the exchange of nonredundant relaying data or scheme data, such as bus differential tripping. A wired contact input on each relay permits blocking of all GOOSE data set transmissions by simply opening a test switch during relay testing or maintenance.

The redundant relaying transmit data sets contain status data, such as maintenance switch status, breaker failure blocking switch status, line reclosing preference, bus test sources, and relay health. Protection data, such as breaker failure initiates, breaker failure lockouts, and transformer lockouts, are also included in this data set. The other transmit data sets contain data for bus differential tripping, breaker failure on a bus breaker, and bus testing after an operation.

3 NETWORKED IEDS IMPROVE SYSTEM CAPABILITIES

The act of integration realizes significant system benefits over traditional methods of measuring multiple field terminations, regardless of the protocol(s) or communications methods used [1]. Systems constructed with integrated IEDs networked via wireless, copper, fiber, serial, or Ethernet connections combined into a local-area network (LAN) offer the following benefits:

- Because of the reuse of data detected by a single IED and digitally communicated to integrated IEDs and other data clients, field terminations, associated wiring, labor, and maintenance are reduced.
- By using IEDs that, in addition to their primary functions, also perform ongoing diagnostics of their own performance and that of the equipment they are monitoring, the quantity of unsupervised process and apparatus functions is reduced.
- Confirming the availability and reliability of the method by which the data are being collected and alarming when the data path is broken, the minimized distance of the unsupervised data path between the field source and data client(s) greatly improves the value of the data.
- Supervision is maximized by replacing traditional, unmonitored copper terminations with monitored digital communications at the IED closest to the field data. This, in turn, detects and alarms communications problems immediately.

4 ESSENTIAL IED-LEVEL TOOLS

Multifunction, microprocessor-based relays incorporate not only multiple relay functions in one box but also include programmable logic capabilities. These logic capabilities allow various logic schemes previously implemented by wiring auxiliary relays, timers, and devices together to be implemented in a single device using settings [2]. The technician and/or engineer tasked with testing or troubleshooting an installation can visualize the logical function as an electrical path on the diagram. However, verifying that messages and the data that they transfer are correctly moving over the Ethernet requires new, specialized tools.

4.1 GOOSE Message Statistics

In order to make GOOSE messages perform adequately, many traditional Ethernet mechanisms had to be removed and, in fact, a new and unique Ethertype had to be created. Each GOOSE message must fit within a single Ethernet frame, so each consecutive message has a unique sequence number incremented by one. The subscribing IED can determine if GOOSE messages are received out of sequence. Each time the message contents change, the message status number is incremented. This allows the subscribing IED to determine which message it has received and if the message payload has changed.

4.2 GOOSE Message Quality Calculation

There are several characteristics that need to be monitored in order to verify the correct publication and subscription of GOOSE messages. The receiving IED needs to verify both the quality of the messages as well as the quality of the data within the messages.

4.3 IED-Supported GOOSE Diagnostic Message

Using the Telnet engineering access port, the GOOSE diagnostics are retrieved directly from the IED to show the configuration and status of incoming and outgoing GOOSE messages. The IED reports shown in Figure 2 display the transmit and receive GOOSE message configuration and performance. It is essential to retrieve these data from the IED directly to correctly verify the message performance at the network interface of the IED rather than using software on a computer connected to another node of the network.

```
#>>GOO

GOOSE Transmit Status

   MultiCastAddr   Ptag:Vlan  StNum       SqNum      TTL
--------------------------------------------------------
       CFG/LLN0$GO$GooseDSet13
   01-0C-CD-01-00-11  4:2     204         63817      953
   Data Set:         CFG/LLN0$DSet13

GOOSE Receive Status

   MultiCastAddr   Ptag:Vlan  StNum       SqNum      TTL
--------------------------------------------------------
       CFG/LLN0$GO$GooseDSet13
   01-0C-CD-01-00-10  4:2     1750        53397      1998
   Data Set:         CFG/LLN0$DSet13
```

```
=>>goo s 1

 SubsID 1
-----------------------------------------------------------------------
 Ctrl Ref:         l_1CFG/LLN0$GO$GOOSEOutPri7
 AppID    : 4119
 From     : 07/13/2012 09:15:40.992  To: 07/13/2012 10:26:47.660

 Accumulated downtime duration                       : 0000:00:00.008
 Maximum downtime duration                           : 0000:00:00.008
 Date & time maximum downtime began                  : 07/13/2012 09:15:41.109
 Number of messages received out-of-sequence(OOS)    : 0
 Number of time-to-live(TTL) violations detected     : 1
 Number of messages incorrectly encoded or corrupted: 0
 Number of messages lost due to receive overflow     : 0
 Calculated max. sequential messages lost due to OOS: 0
 Calculated number of messages lost due to OOS       : 0
```

Figure 2 GOOSE verification statistics and GOOSE performance statistics

4.4 GOOSE Message Failure Alarm and Notification

The subscribing IED calculates GOOSE message quality for each incoming GOOSE message. Because these methods are standardized, each IED is capable of calculating the GOOSE message quality for GOOSE messages from any manufacturer IED.

Once the IED has calculated the GOOSE message quality status, this value is available as a logic element within the IED. Each IED uses this status to block and enable logic, display GOOSE status on the IED front panel to aid troubleshooting, and send an alarm to technicians via SCADA protocols or email, text message, or telephone messages. The change of status is also time-stamped and recorded as an SER report.

5 CONCLUSION

Using new IEC 61850 client-server methods to replace traditional master-slave methods was accomplished without making major changes to the previously designed HMI and SCADA interfaces. PLCs were easily replaced with an IED network and communications processor by using more functionality available in the IEDs. Software tools were developed by PPL to accommodate new engineering and testing practices. During the software design process, special considerations were made with regard to system expansion, troubleshooting, and maintenance of the system. It was important to PPL that the system was easy to expand, test, and maintain.

Messaging interoperability between peers depends on the device properties and the system architecture. Commissioning tests must be performed to verify that the communications behavior of a device as a system component is compatible with the overall network design. Standalone network test devices, HMI applications designed to observe network messaging, and internal IED diagnostics are all essential to configure, verify, and troubleshoot network communications.

The most important lesson learned is the need to choose IEDs and network technology that support and simplify communications interface testing. Take the following actions for successful commissioning and ongoing maintenance activities:

- Choose IEDs that respond to commands to identify which configuration file is loaded within the IED and in use.
- Choose IEDs that respond to commands to identify the status of configured outgoing GOOSE message publications.
- Choose IEDs that respond to commands to identify the status of subscription to expected incoming GOOSE messages.
- Choose IEDs that provide real-time GOOSE transmit and receive status and statistics.

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