Testing a Live Industrial Digital Substation with IEC 61850 Tools

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Abstract

In 2023 Rivian commissioned an IEC 61850 digital switchgear lineup which included voltage and current sensors instead of conventional PTs (potential transformers) and CTs (current transformers). These sensors necessitated the integration of IEC 61850 Sampled Values and IEC 61850 GOOSE messaging to achieve the required protection and control schemes.

POWER Engineers reviewed the schemes, created commissioning test plans, and executed those test plans at the plant. Testing included the use of IEC 61850 specific testing tools from multiple vendors. Automated test plans were created in the testing tools which allowed us to perform this testing extremely efficiently.

One challenge for this testing was that at least one of the two buses had to remain in service during testing to feed the plant. Great care was taken to develop the test plans in a way that one bus could be tested without disturbing the other. The team relied heavily on the virtual isolation features of IEC 61850 to accomplish this goal.

This paper provides an in-depth review of how the switchgear was tested, testing equipment and software tools used, how each tool was used and the rationale for each tool selection. It also describes how the verification of proper operation was done, system behavior under failure conditions, and how the simulation of contingencies was performed.

Finally, the paper will capture key takeaways and lessons learned from the project.

Introduction

Recently at Rivian's Normal, IL production facility, a medium-voltage switchgear lineup was installed as part of expanded production. The switchgear consists of two main breakers, a bus tie, and two busses each with 18 feeders and one capacitor bank. All protective relays supported IEC 61850 Ed2 and used GOOSE messaging to implement various protection schemes.

The scope of the commissioning performed by POWER Engineers, Inc. (POWER) and ABB included network testing, time synchronization testing, Sampled Values (SV) testing, and testing of IEC 61850 GOOSE-based protection schemes (Bus and Breaker Failure protection). Main-Tie-Main interlocking logic was also tested.

In addition to the IEC 61850 GOOSE messaging component of the protection design, it is worth noting a few nuances. Conventional potential transformers and current transformers were not installed. Low-energy voltage sensors and current sensors were used in the design instead. Voltage sensors were installed at a few select locations to meter the bus voltage. IEC 61850 Sampled Values (SVs) was implemented to publish the bus voltage to all protective relays on the respective bus. The use of SVs required Precision Time Protocol (PTP) for protective relay time synchronization due to the high frequency of data transmission.

Finally, all protective relays supported and used Parallel Redundancy Protocol (PRP). Commissioning scope also included verifying the PRP network architecture.

No SCADA system had yet been implemented with this switchgear, so we did not have any means for visualizing or historizing data. The complexity of commissioning was further increased with the requirement of testing one bus while the other bus remained energized. To ensure our testing would not inadvertently trip an in-service breaker, IEC 61850 test mode was used. To further assist in validating IEC 61850 settings and capturing test results, a variety of third-party hardware and software was used.

System Single Line Diagram

The figure below shows a single line diagram of the switchgear under test. Bus 300 was the first bus to be commissioned while Bus 400 remained in service. The bus tie breaker was racked out for safety purposes. The bus tie cubicle had two relays: the first relay provides overcurrent, voltage and synchro check functions. This relay is programmed with core logic of the ATS system.

The second relay is programmed with the core logic of the IEC61850 communication-based Bus and Breaker Failure protection scheme. The function of this relay in this scheme is to process operation information from all contributing relays via GOOSE communication.

The protective schemes under test were bus protection, breaker failure, and a main-tie-main interlock scheme. The ultimate outcome of the bus protection and breaker failure schemes was to trip all feeder breakers if (1) a bus fault was detected or (2) a feeder breaker failed to trip open and clear a fault on the feeder. The trip signals for both schemes were transmitted by the bus tie logic processor which was responsible for sending GOOSE messages with trip signals to both Bus 300 and Bus 400. Therefore, it was extremely important to ensure no trip signals would be published via GOOSE messaging and processed by the subscribing relays on the energized bus. IEC 61850 test mode was used for this purpose.

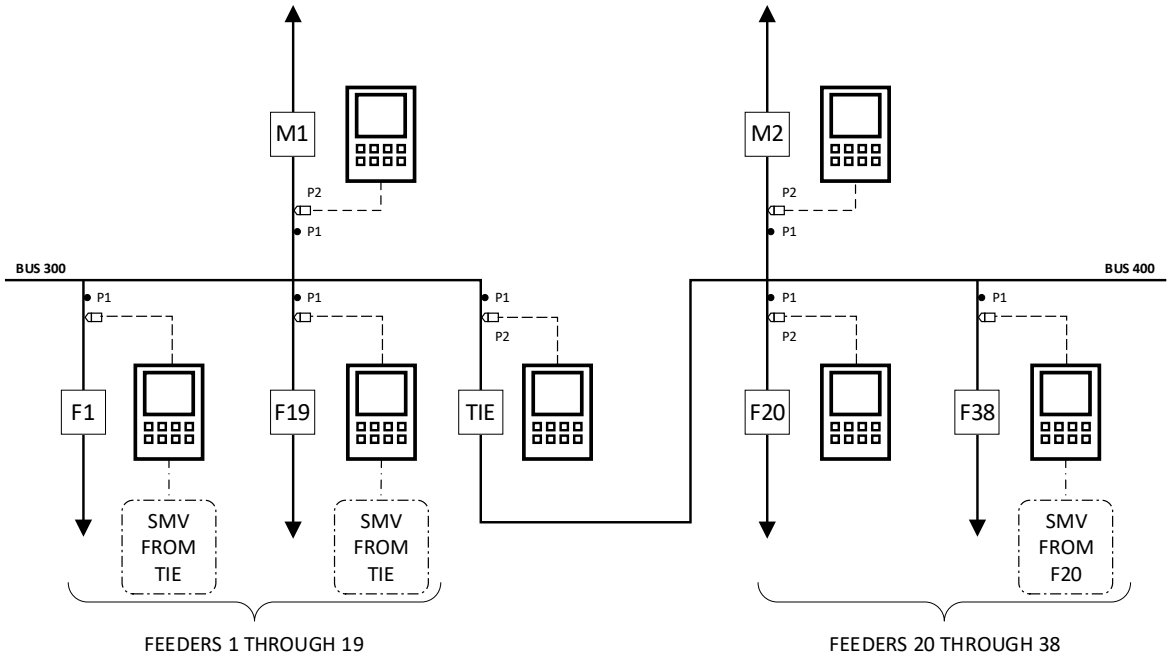

Figure 1: System Single Line Diagram

IEC 61850 Test Mode

Per the IEC 61850 standard, a vendor's implementation of test mode may allow for individual logical nodes to be put into test mode. However, this was not the case for the protective relays under test in our system. The implementation of IEC 61850 test mode was for the entire logical device. The protective relays allowed GOOSE messages to be processed if both the publishing and subscribing devices were operating in the same mode. If the publishing protective relay was in test mode and the subscribing protective relay was in normal mode, the GOOSE message would not be processed by the subscriber. If both relays were either in normal mode or in test mode, the GOOSE message would be processed within the relay logic.

Preliminary testing was performed to ensure our understanding of test mode implementation met reality. Once our testing confirmed this understanding we could safely and confidently proceed testing the first bus of switchgear while the other bus remained energized.

Testing Hardware

Two three-phase sets required for commissioning. Additional hardware was also used specifically for IEC 61850 testing and the current and voltage sensing devices.

Voltage and Current Sensors

The current and voltage sensors both transmit a low-voltage signal over an ethernet cable to the protective relay. The rear interface of the test switches had six RJ45 ports: three for the sensor inputs and three for the relay inputs. It is important to note that the secondary signals for current and voltage are transmitted on the same ethernet cable, therefore, only three cables are needed: one for each phase. Special adapters were used to transmit the low-level signal from the test set to the three ethernet cables required for each secondary signal. See the figure below for more details.

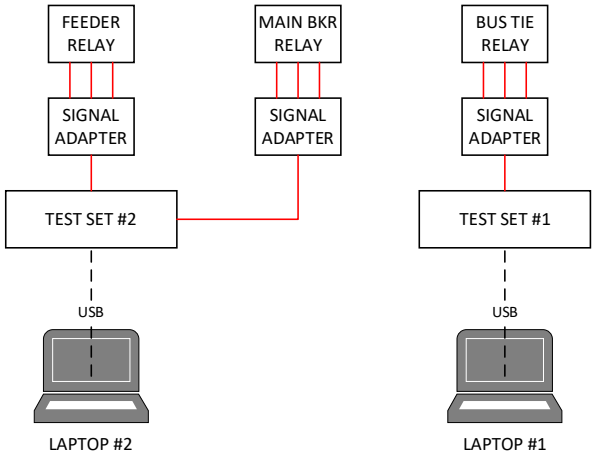

Figure 2: Three-phase test set connections for voltage and current sensor simulation

IEC 61850-specific hardware

Specialized hardware was also used to commission IEC 61850-related settings. A network analyzing device, with PRP capability, was connected to both PRP LAN A and LAN B of the bus under test. The IEC 61850 SCD file was loaded onto the network analyzer. Specific devices were selected to be verified, then the network analyzer compared the selected CID files with all CID files found on the network. Differences were flagged in the network analyzer's software. Using this tool allowed for fast and dependable verification of IEC 61850 settings loaded on the relays versus the settings files for the relays.

The network analyzer was also capable of analyzing the Precision Time Protocol signal. The network analyzer determined the grandmaster clock MAC address. The software also checked the LTMS logical node for each protective relay on the network and identified the grandmaster clock MAC address. Failing over from the top-priority master clock to the second-priority master clock was easily captured using the same method. Software screenshots were taken for the commissioning record. The figure below shows the physical setup of the network analyzer for these tests.

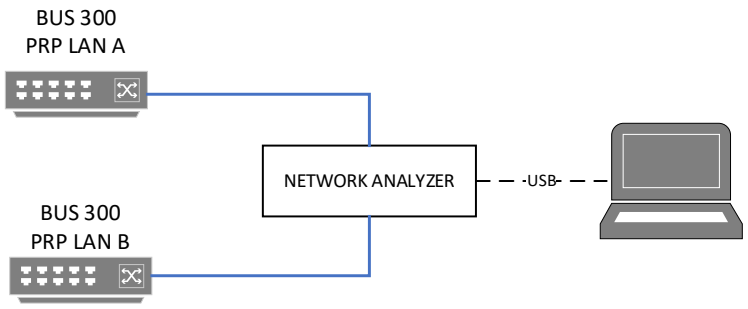

Figure 3: Network Analyzer Architecture

Testing Software

Most test results were captured using a single piece of third-party software. Like the network analyzer, this software was also capable of verifying the IEC 61850 CID files, however we did not need to repeat that test. The figure below shows our typical test setup. Two laptops were used, each with a serial USB connection to a three-phase test set. One laptop had the third-party software installed for capturing IEC 61850-related test results. Despite the network switch connections between Bus 300 and Bus 400, we were confident GOOSE messages would **not** be processed by the protective relays on the energized bus.

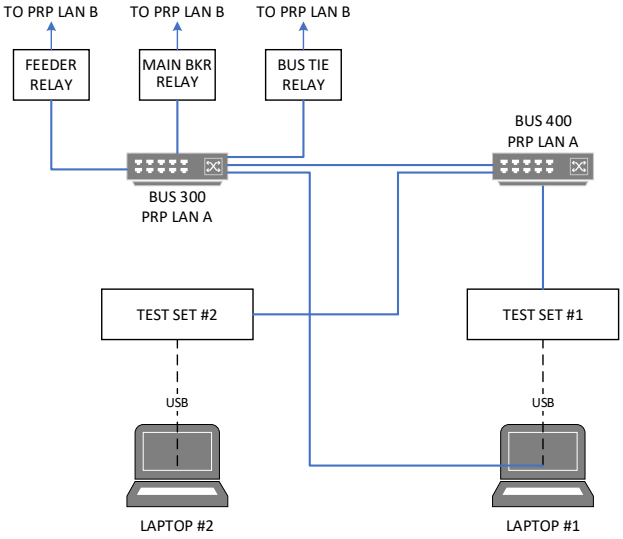

Figure 4: IEC 61850 Testing Network Architecture

Sampled Values

A portion of the commissioning required verifying Sampled Values subscription by all protective relays. Using the third-party software, all of the MMXU logical nodes with phase voltages could be viewed at once. The magnitude, angle, and quality of the data was clearly displayed. This allowed a simple screenshot to record all relays successfully subscribing the SV messages. Additional testing was performed for Loss of Potential with similar results captured in the third-party software.

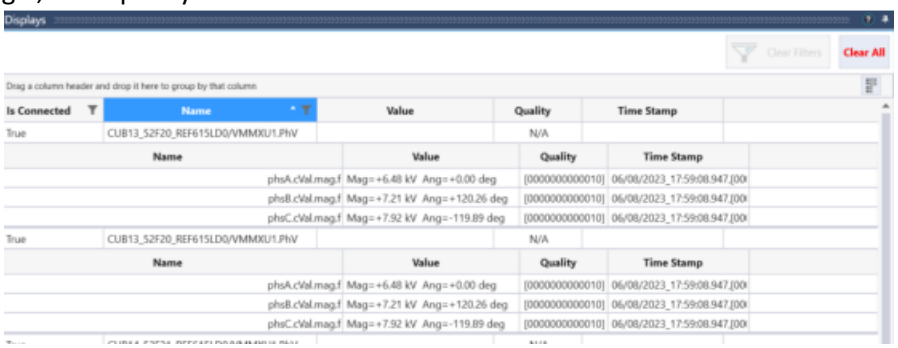

Figure 5: Sampled Values Verification Screenshot

Protection Schemes

The primary focus of the commissioning were the protection schemes. These schemes were still tested by injecting secondary voltage and current for both nominal conditions and fault conditions. Numerous test sequences were developed to streamline the repeatability of this testing.

The new feature, however, was capturing IEC 61850 data in a graphical format using third-party software. The user would select specific relays to capture data from, begin recording in the software, and stop recording once the fault sequence was complete. Then the user could select specific IEC 61850 data attributes and graph these on the same screen. Since all the relevant data point were binary, the graphs simply showed values going from 0 to 1 or 1 to 0. However, the software allowed for displaying a trip signal generated from one relay, received by all the feeder relays and the feeder breakers all opening at the same time. Normally this information could be captured in Sequence of Event logs with the timestamp of all data, but this graphical representation allowed flexibility in choosing which data attributes were graphed and the results were easily readable.

The example screenshot below is from breaker failure testing. This shows the 50BF LED asserting on a feeder relay, the BF transfer trip signal asserted in the feeder relay, the 50BF Received LED asserting on the feeder relay and the BF trip signal transmitted by the tie relay processing all GOOSE messages.

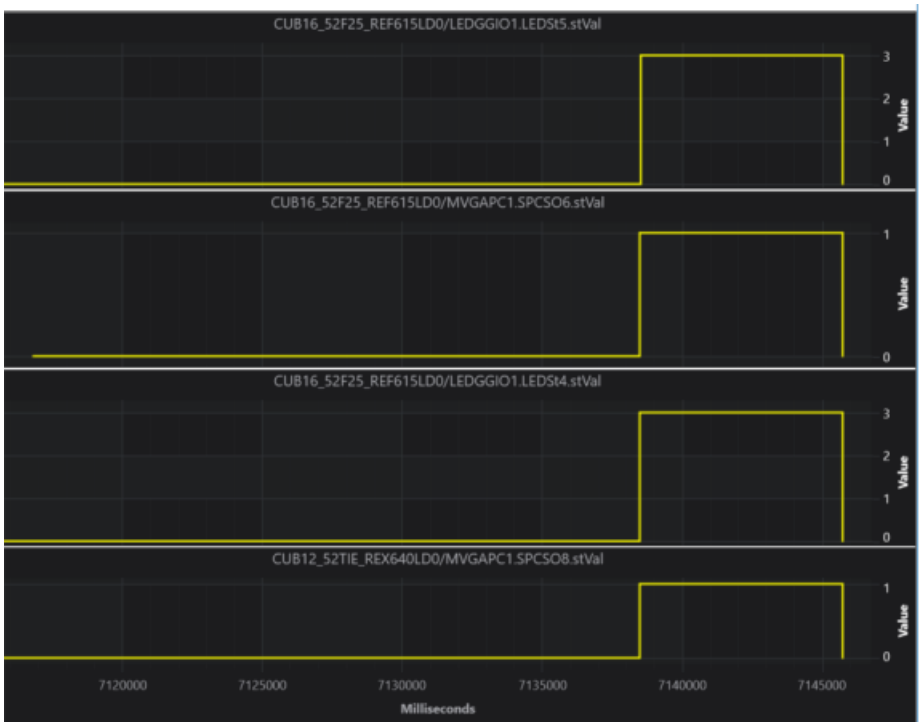

Figure 6: Breaker Failure Test Screenshot

Lessons Learned

It is important to note that conventional verification of CID file settings, GOOSE communication, PTP communication, and protection elements is done using front panel LEDs, display points, Sequence of Events recording, or other means requiring navigating through a front panel display to find a specific value. Using these tools quickly provided results and indicated any errors. Recording of the results was as simple as screenshots of the software providing all the necessary detail to verify GOOSE and PTP communication throughout the ethernet network and proper execution of the protection schemes.

During commissioning we encountered a problem with time synchronizing the test sets using PTP. Ultimately, we found a workaround using a single test set that did not require time synchronized test sets. The system did not have a dedicated GPS/GNSS clock which would have simplified the test set time synchronization. In retrospect we should have included a GPS/GNSS clock in our testing hardware to mitigate that risk.

Finally, and most important was the use of IEC 61850 test mode. Though the implementation placed the entire logical device into test mode, this was still an invaluable tool allowing us to safely and efficiently test one bus while the other bus remained energized.

Bios

Aaron Cowan is a Lead Engineer for POWER Engineers, Inc. with over 10 years of experience designing, implementing, and field testing SCADA and automation system. This experience includes industrial, large and small utilities, and renewable systems. Prior to working at POWER, Aaron worked at SEL in Pullman, WA. Aaron has a master's degree in electrical engineering from the University of Idaho.

Eduardo Colmenares is a Senior Project Lead Engineer for ABB Digital Solutions Center with over 36 years of experience in the field of Protection and Control. He has been working for ABB US since 2010. Previously, he worked for 15 years in ABB Venezuela where he held several positions including Country Service Manager, BAU Manager for Protection & Substation Automation, BAU Manager for Power Generation and BAU Manager for Utility Communications. Also, he worked 5 years for an Electric Utility with a focus on protection and control. Eduardo has authored or co-authored several papers for Relay conferences. Eduardo has an Electrical Engineering degree from Universidad de Los Andes, Merida, Venezuela in 1987.

Keith Gray received his M.S. in Electrical Engineering from Southern Illinois University Edwardsville in 2005. He is a protection, automation, and control engineer with 18 years of experience working for POWER Engineers. He has focused on digital substations and IEC 61850 since 2014 and contributes to the IEC 61850 standards via IEC TC57 WG10. He is currently participating in Cigre working group B5.68 covering the IEC 61850 engineering process. He is a licensed Professional Engineer in the state of Idaho.