TITLE: UNLOCKING TURNKEY IEC 61850 PROJECTS: PART 2 – PROGRAMMING AND FACTORY ACCEPTANCE TESTING (FAT)

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ABSTRACT

Continuing the IEC 61850 multi-part series, Part 2 delves into the programming (configuration) and Factory Acceptance Testing (FAT) stages of turnkey substation projects. It outlines how intelligent electronic devices (IEDs) and systems are configured using standard IEC 61850 tools and files to achieve multi-vendor interoperability, and how comprehensive off-site testing ensures a seamless integration before deployment. Key technical insights include the use of Substation Configuration Language files (.ICD, .CID, .SCD) to unify device configuration, and best practices in setting up IED communication and logic. The paper also contrasts greenfield (new installation) versus brownfield (retrofit) project considerations, highlighting case studies of each to demonstrate challenges and solutions in real-world scenarios. Critical importance is placed on conducting thorough FAT – assembling and testing the entire system in a controlled environment – to validate functionality and performance. Lessons from projects that underutilized FAT underscore the risks of inadequate testing, while an examination of FAT intensity trade-offs guides practitioners in balancing thoroughness with project constraints. Finally, post-FAT deployment steps are discussed to ensure a smooth transition to on-site commissioning. This condensed paper maintains essential technical explanations and case study insights, providing a clear and concise guide to effectively program and test IEC 61850 systems as part of a successful turnkey implementation.

INTRODUCTION

Part 1 of this series ("Engineering Insights") established the foundation of IEC 61850 in modern substation automation, focusing on engineering design principles, system architectures, and integration challenges. In Part 2: Programming and FAT, the focus shifts from design to implementation – translating engineered designs into configured devices and validating the entire system's performance before site installation. A core theme is the transition from traditional hard-wired schemes to IEC 61850's communication-based architecture. In conventional protection and control systems, each signal or interlock might require dedicated copper wiring; by contrast, IEC 61850 leverages high-speed communications (GOOSE messages and sampled values) to exchange status and control signals over Ethernet networks. This paradigm shift greatly reduces physical wiring and installation labor, but it increases the importance of meticulous system programming (i.e. digital configuration) and testing.

This paper addresses how to effectively program an IEC 61850-based system to ensure multi-vendor interoperability, reliability, and cyber-secure operation, aligning with the fundamental pillars introduced in Part 1. It then delves into Factory Acceptance Testing (FAT) – a critical practice in which the integrated system is assembled and tested in a factory or lab setting to verify that all components work together as intended. We discuss how these steps differ in greenfield vs. brownfield projects, as each presents unique challenges. Real-world case studies (a new substation and an existing campus microgrid retrofit) illustrate the programming approach and FAT process, demonstrating how thorough preparation can lead to successful outcomes. Finally, we consider the consequences of insufficient testing through examples and provide guidance on balancing an intensive FAT with practical project constraints. Part 2 thus provides a comprehensive look at the execution phase of turnkey IEC 61850 projects, bridging the gap between engineering design and on-site commissioning (to be covered in Part 3).

PROGRAMMING IEC 61850 SYSTEMS – OVERVIEW AND KEY COMPONENTS

Programming in the context of IEC 61850 refers to configuring the various IEDs and network components so that they communicate and operate according to the engineered design. Rather than writing lines of software code, this “programming” is largely accomplished by setting parameters, defining datasets, and establishing communication links using standardized configuration files and tools. The goal is to ensure that each device (from protection relays to HMI displays) knows what data to exchange, what logic to execute, and how to respond within the integrated system. Key components that require configuration in a typical IEC 61850 project include:

- **Protection & Control Relays (IEDs):** These are configured with settings for protection functions (e.g. overcurrent thresholds), control logic (interlocks, tripping schemes), and communications (publishing/subscribing GOOSE messages, reporting measurements via MMS). Each relay must be programmed to recognize data from other devices (such as breaker statuses or interlocks from peer relays) and to send its own data to the network as needed.
- **Remote Terminal Units (RTUs) / Data Concentrators:** In some systems, RTUs or data concentrator devices aggregate data from multiple IEDs and act as a gateway to SCADA or EMS (Energy Management Systems). For IEC 61850 implementations, these units are configured to subscribe to IED data using MMS (Manufacturing Message Specification) reports or GOOSE, rather than polling discrete I/O. They ensure legacy systems or control centers can receive the needed data from the IEC 61850 network.
- **Human-Machine Interfaces (HMIs):** HMIs (such as substation SCADA screens or operator workstations) need configuration to display real-time data from IEDs (breaker positions, analog values, alarms) and to send control commands. Under IEC 61850, HMIs interface via standard protocols (MMS reports/controls), so the HMI must be programmed to interpret the data model of each IED (using standardized naming from the configuration files) and present a cohesive user interface.
- **Network Switches and Infrastructure:** While not “IEDs” in the classical sense, the managed Ethernet switches that form the substation network are a vital part of the system. They must be configured for proper VLANs, quality of service (QoS), IGMP snooping (for multicast GOOSE traffic), redundancy protocols (like PRP or HSR if used), and cyber-security features. Proper network configuration ensures the IEC 61850 messages are delivered reliably and with low latency between devices.

Each of these components must be configured in harmony so that the overall system operates correctly. This is achieved through careful planning and use of IEC 61850’s Substation Configuration Language (SCL) files, as described next.

UTILIZING IEC 61850 CONFIGURATION FILES (.ICD, .CID, .SCD)

A cornerstone of IEC 61850 system programming is the use of standardized XML-based configuration files defined by the standard. These files enable a vendor-neutral representation of device capabilities and system configuration, which is crucial when multiple manufacturers’ devices must work together. The main file types are:

- **IED Capability Description (ICD):** An ICD file is provided by the device manufacturer. It describes the capabilities and data model of a given IED type (for example, all the logical nodes, data attributes, and communication services the device supports). Think of the ICD as a template or library file defining what the device can do, without yet specifying the project-specific settings. System integrators import ICD files for each device model into a configuration tool when designing the system.
- **Substation Configuration Description (SCD):** The SCD file represents the entire substation (or system) configuration. It is created by the system integrator using an IEC 61850 configuration tool (often provided by a vendor or a third-party tool compliant with the standard). The SCD combines all the relevant IED definitions (from their ICDs) and adds project-specific details: the single-line diagram of the substation (logical connections between switchgear and IEDs), the assignment of logical node addresses, datasets and report control blocks for MMS, GOOSE control blocks

(publishing and subscribing between IEDs), and communication network settings. Essentially, the SCD is a master plan that defines how every device is interconnected logically.

- **Configured IED Description (CID):** A CID file is effectively the specific configuration for one IED extracted from the overall SCD. Once the system design is complete in the SCD, a CID file can be generated for each IED, containing only that device's configuration (its logical node instances, datasets, communications, etc. as per the system design). This CID file is then loaded into the actual IED via the vendor's configuration tool or interface, programming the device with the exact settings it needs to function in the system.

Using these files, an integrator can design the system once (in the SCD) and then distribute the configuration to all devices, rather than programming each device in isolation. This promotes consistency and reduces errors, since the SCD ensures that, for example, if Relay A is supposed to send a GOOSE message for "breaker X open" and Relay B is to receive it, both will have matching configurations generated from the same source. In practice, engineering tools validate the consistency of these connections (e.g., a subscribing logical node expecting a dataset that a publisher provides in the SCD).

It is worth noting that vendors implement IEC 61850 configuration with slight differences: some relay vendors allow building the entire SCD and loading it through their own software, while others rely on third-party system configuration tools. Despite these differences, the SCL files provide a common language to coordinate multi-vendor systems. The engineering team must often merge configurations from different sources, requiring diligence to maintain interoperability and avoid mismatch in definitions. Once all IEDs are configured and their CIDs loaded, the project moves to thorough testing to validate this configuration – which is where Factory Acceptance Testing comes into play.

FACTORY ACCEPTANCE TESTING (FAT) FOR IEC 61850 SYSTEMS

After programming the IEDs and network, Factory Acceptance Testing (FAT) is conducted to verify the system's integrity and performance in a controlled environment before field installation. FAT is a critical phase in any turnkey project, but it is especially important for IEC 61850 systems because of their complexity and the reliance on digital communication. In an FAT, the goal is to assemble and simulate the entire system as closely as possible to real operating conditions, so that any issues can be identified and resolved early. This prevents costly and risky troubleshooting at the site and gives all stakeholders confidence in the design.

FAT Objectives and Scope: At its core, FAT aims to answer the question, "Will the system work as intended once installed?" This includes verifying protection tripping logic, control sequences, communications, failover behaviors, and overall performance under normal and abnormal conditions. It's an opportunity for engineers and end-users (such as utility or plant operators) to witness and confirm the functionality against the specifications. For an IEC 61850 project, FAT typically encompasses testing of GOOSE message exchanges, MMS data reporting to SCADA, HMI displays and controls, relay protection function responses, and network redundancy mechanisms.

Typical FAT Process: The FAT procedure is usually tailored to each project, but key steps and tests often include:

1. **Physical Setup and Wiring Checks:** All new devices (relays, RTUs, HMIs, network hardware, etc.) are mounted and powered in a lab environment. The devices are interconnected through the network switches as per the design topology. Any necessary physical wiring (for example, wiring to terminal blocks for I/O simulation or between devices for legacy signals) is completed and verified. Even in IEC 61850 systems, some conventional wiring may exist (for instrument transformers, backup hardwired trips, etc.), which must be checked for continuity and correctness.
2. **Configuration Verification:** The correct versions of configuration (CID) files are installed in each IED, and a system-wide verification is performed. This may involve using IEC 61850 test tools to ensure that each device is communicating (e.g., all GOOSE publishers have subscribers, all MMS reports are received by the data concentrator or HMI, etc.). Essentially, this step validates that the digital data flow configured in the SCD is active and without errors (no missing GOOSE, correct datasets, etc.).

3. **Signal Injection and Functional Testing:** With the setup ready, testers inject simulated signals to exercise the protection and control functions. For instance, secondary injection test sets can feed analog values to a relay (simulating voltage or current magnitudes) to trigger protection trips. Alternatively, logic test software might directly trigger a logical node. The response of the system is observed: did the correct GOOSE messages publish? Did the receiving IED take the expected action (e.g., open a breaker in the simulation)? Are alarms correctly shown on the HMI? This step often uses predefined test scenarios to methodically check each protection element and interlock.
4. **Integration and Interoperability Testing:** Beyond individual device function, the FAT will test end-to-end sequences involving multiple devices. For example, a complete breaker failure scenario might be executed: a fault is simulated, the primary relay trips and sends a GOOSE message, the backup relay receives it and issues a trip, and the HMI logs all events. Multi-vendor interoperability is closely observed here – e.g., ensure that a GOOSE message from Vendor A's relay is recognized by Vendor B's relay. Any incompatibilities or timing issues in communication must be addressed at this stage (often by adjusting configurations or, if needed, firmware).
5. **Performance and Stress Testing:** In critical systems, testers may also evaluate performance metrics. This can include timing tests (measuring GOOSE message propagation delay and relay trip times to ensure they meet requirements), network stress tests (saturating the network with background traffic or disabling one network path if using redundancy like PRP, to ensure failover is seamless), and checking behavior under error conditions (unplugging one network cable to verify the other redundant path carries messages without loss). Cybersecurity features might also be validated – for instance, confirming that only authorized devices can connect, and that the system responds to a simulated unauthorized access attempt.
6. **Security and Compliance Checks:** If the project has specific compliance requirements (NERC CIP for cybersecurity, IEC 61850-10 for conformance, etc.), the FAT is a point to perform those tests. This might involve certificate-based authentication tests for devices, verifying security logs, or ensuring the system meets any regulatory standards before going live.
7. **Documentation of Results:** Throughout the FAT, detailed records are kept of each test case, expected result, and actual outcome. Any discrepancies or failures are noted and corrected by adjusting configurations or hardware as needed, then re-tested. The final outcome of FAT should be a punch-list of issues resolved and a formal FAT report that is signed off by both the integrator and the client, indicating that the system, as tested, meets the design specifications.

Conducting such a thorough FAT can be time-consuming (often spanning several days or weeks or months depending on system complexity), but it dramatically reduces the risk during field commissioning. In many cases, a successful FAT means that when the system is installed on-site, it can be up and running with minimal adjustments. The next section examines how the approach to programming and FAT can differ between new-build projects and retrofits.

IMPLEMENTING IEC 61850 IN GREENFIELD VS. BROWNFIELD PROJECTS

The context of a project – whether it is a greenfield installation (a brand-new facility or substation) or a brownfield project (an upgrade or expansion within an existing, live facility) – influences the strategy for both programming and FAT. IEC 61850 is beneficial in either scenario, but the challenges and priorities differ.

Greenfield Projects: Starting from Scratch

In a greenfield project, engineers have the advantage of a blank slate: the substation or plant is being built anew, which means fewer constraints from previous systems. The IEC 61850 design can be optimized from the ground up. Key characteristics and strategies for success in greenfield implementations include:

- **Clean Slate Design:** With no legacy control wiring to accommodate, the design can fully embrace IEC 61850 communication. Protection and control schemes may be implemented entirely with GOOSE messaging for interlocks and trips, reducing physical wiring dramatically. The system architecture (such as network topology and IED placement) can be designed for optimal performance and future scalability without needing to fit into existing arrangements.
- **Standardization and Multi-Vendor Integration:** Greenfield projects often involve multiple vendors' equipment. Early in the project, choosing devices that are truly IEC 61850 compliant and interoperable is crucial. The integration team can standardize on certain models or require conformance certificates to minimize integration issues. All chosen IEDs' ICD files are collected and used to build the master SCD. The team might perform interoperability tests on a small scale (like connecting one of each type of device) early to iron out any issues before full programming.
- **FAT Focus – Design Validation:** For greenfield systems, the FAT serves as the first time the entire new design is realized. Since there is no existing system to compare against, emphasis is on validation that the new protection and control schemes work as intended. During FAT, engineers often discover logic improvements or setting adjustments that can enhance the system – for instance, tuning coordination between protective devices or refining alarm logic. These can be incorporated before deployment. The FAT also provides an opportunity to train operators on the new system's HMI and behavior, since everything is new to them.
- **Schedule and Risk Management:** While greenfield projects don't have the complication of keeping an existing system running, they often are under tight construction schedules. Aligning the FAT with construction timelines is important – equipment must be available in time for FAT, and FAT must finish in time to ship and install the equipment. Thorough FAT in a greenfield project helps avoid delays in energizing the new substation, as commissioning can proceed more smoothly.

In summary, greenfield IEC 61850 implementations thrive on upfront planning and utilizing the freedom of a fresh design. The main challenge is ensuring that a design that looks good on paper (or in an SCD file) actually performs in the real world – which the FAT is designed to prove.

Brownfield Projects: Upgrading Existing Systems

Brownfield projects involve adding IEC 61850-based controls to an existing substation or power plant. These are inherently more complex because new digital systems must coexist or replace old infrastructure with minimal disruption. Key characteristics and strategies for brownfield implementations include:

- **Integration with Legacy Systems:** Often the new IEC 61850 IEDs have to interface with legacy devices that may not support IEC 61850. This could involve using protocol converters or I/O modules to transition between old, hardwired signals and new GOOSE messages. For example, if an existing electromechanical relay remains in service, a new IEC 61850 relay or an IO device might be used to sense its trip and broadcast a GOOSE message, or vice versa. The programming must account for these hybrid interfaces.
- **Phased Cutover and Commissioning:** A critical strategy in brownfield projects is sequencing the installation and cutover to avoid long outages. Portions of the system are upgraded in stages. The new IEDs might be installed in parallel with the existing system before fully switching over. During

this interim period, the new system could be running in monitoring mode or partially active mode. IEC 61850 greatly aids this approach: because signals can be shared via network, the new equipment can be connected to the running system with minimal physical disturbance. For instance, new relays can subscribe to GOOSE messages from temporary simulators or from old system proxies to test functionality, then later simply be switched to live inputs. Careful programming is needed so that when the final cutover happens (e.g., enabling tripping from the new relays), it is just a configuration toggle rather than a complete rewire.

- **FAT Focus – Regression Testing and Compatibility:** In a brownfield FAT, the team not only validates the new system's performance, but often they also simulate the presence of the existing system. This means testing scenarios where parts of the scheme are still handled by old equipment. For example, if during the transition some interlocking signals are still hard-wired between old relays and new relays, the FAT setup should replicate that wiring to test interactions. Another focus is ensuring that the overall protection coordination and automation logic remains correct when transitioning from old to new – essentially **regression testing** against the previous scheme's behavior to guarantee the upgrade doesn't introduce any unintended gaps in protection or control.
- **Minimal Downtime and Risk Mitigation:** Because the facility is usually operational, any mistakes can cause unplanned outages. Therefore, FAT and offline simulations carry even greater importance – they must catch issues that could not only delay commissioning but potentially cause a system trip if something was overlooked. Redundancy and fallback plans are often in place: for instance, if the new digital scheme fails to perform during a live test, the old system can be kept in service until the issue is resolved. The programming of the new system might include contingency modes (as was the case in a campus microgrid project, where the new control scheme could revert to the original configuration if certain conditions weren't met.

In summary, brownfield IEC 61850 projects demand careful choreography between old and new. The programming must accommodate a transition period and possibly unconventional interfaces, and the FAT must be as comprehensive as possible to simulate real operating conditions. When done successfully, the result is an upgraded system that achieves modern performance without interrupting the critical services of the existing infrastructure.

CASE STUDIES

To illustrate the above concepts, this section presents two case studies drawn from actual projects: one greenfield and one brownfield. Each case study highlights how IEC 61850 programming and FAT were applied, the challenges faced, and the outcomes achieved.

Case Study 1: New Substation Implementation (Greenfield)

Project Overview: A utility undertook a project to construct a new 115 kV transmission substation to improve grid reliability in a growing region. The substation was designed from the outset to leverage IEC 61850 for all protection, control, and automation. Multiple vendors supplied IEDs: protective relays, data concentrators, station HMI and gateway. The design included a fiber Ethernet network connecting all devices, with PRP (Parallel Redundancy Protocol) implemented for zero-packet-loss network resilience. No conventional control cables were run between devices; all interlocks and tripping signals were engineered as GOOSE messages. To mitigate risks, the project team opted to perform an enhanced FAT, with the design team working closely with the integration, operation and field teams to ensure a polished final product.

Programming and Configuration: The engineering team gathered ICD files from each vendor and used a system configuration tool to create the SCD file for the entire substation. They defined logical nodes for each primary apparatus (breakers, disconnects, transformers) and mapped the required control and indication functions. For example, each bay control unit was programmed to publish a GOOSE message when its breaker was open or closed, and the protective relays subscribed to these to incorporate breaker status into their permissive trip logic. The HMI was configured via the SCD to generate one-line displays and alarm lists, taking advantage of standardized naming from IEC 61850. Custom logic blocks were implemented in the relays for scheme coordination.

FAT Execution: The FAT for this project was conducted at the substation control enclosure manufacturer's facility, where all the AC/DC systems, control panels, IEDs, network, HMI and SCADA equipment were fully constructed. This included the remote input/output (RIO) devices used at the field equipment for all I/O and trip/close commands. To simulate the actual substation, all the RIO's were networked via fiber optic cables to the control enclosure as if they were installed in the field. The test setup included relay test sets injecting currents and voltages to simulate faults, as well as simulation of SCADA/master connections to the gateway. Step by step, the integrator and utility engineers verified each protection function and control action:

- They simulated overcurrent and fault scenarios to ensure proper relay operation and tripping of the correct breakers. The inter-device GOOSE messaging was observed to confirm, for instance, that an upstream relay's trip was received by downstream devices for blocking as intended.
- Loss of communication on one PRP network path was tested by disconnecting one network switch, and it was confirmed that all devices seamlessly continued communicating on the alternate path (with no loss of GOOSE messages or report data).
- The HMI displays were reviewed by operators; points were toggled (via simulated inputs or forcing signals in relays) to check that every indicator and alarm on the screen was correctly driven.
- A timing test was performed where a fault was injected and the time from fault inception to breaker trip was measured and found to meet the substation's clearing time requirements.

Challenges and Solutions: During the FAT, many configuration issues were uncovered, which is expected with the fleet's first iteration of IEC 61850. Hundreds of integration, logic and settings issues were logged and resolved during the FAT. Of particular note was the amount of time it took to get the network operational and properly communicating. The use of multiple equipment manufacturers proved challenging at some points to ensure proper configuration and operation. This task involved weeks of reconfiguration and retesting to ensure the latest and most up to date settings and configurations were in place and tested simultaneously. Utilizing a comprehensive, live testing document allowed for the teams to streamline logging deficiencies, finding their corrective actions, performing the updates and then retesting the system. These kinds of adjustments underscore the value of FAT; all were resolved in the control enclosure manufacturer's facility.

Outcome: The FAT was completed successfully, and the substation equipment was shipped to site with high confidence. During the time the FAT was performed the substation equipment was being set in place, allowing for parallel work to be performed, drastically reducing site time. Indeed, when the substation was energized, it experienced a trouble-free commissioning. No protection misoperations occurred during initial energization and subsequent early operations. The client reported that having fully tested the system in advance shortened the on-site commissioning by an estimated 50%, since all major issues had already been ironed out. This case demonstrated that even a complex new installation with multi-vendor IEC 61850 components can be commissioned smoothly when robustly programmed and tested beforehand.

Case Study 2: Campus Microgrid Upgrade (Brownfield)

Project Overview: An existing medical campus, including a cogeneration power plant and multiple hospital and research buildings, underwent a major upgrade to transform it into a modern microgrid. The campus had legacy protection and control systems that were a mix of discrete relays and PLC-based controls for load shedding and generator dispatch. The upgrade introduced IEC 61850-based IEDs throughout eight medium-voltage switchgear line-ups, integrating them with the plant's generators and the utility connection to enable dynamic islanding (isolating from the utility during disturbances) and fast resynchronization. This was a brownfield project – the hospital campus power could not be interrupted beyond short-planned outages, so the new system had to be implemented in parallel with the old and cut over seamlessly.

Programming and Configuration: The engineering team designed the new control schemes to take advantage of GOOSE messaging for rapid inter-device communication. For example, when a utility disturbance is detected (under-voltage/under-frequency), the scheme sends GOOSE commands to open the tie to the utility and adjusts generator controls to pick up campus load. The existing load shedding scheme was minimized due to the rapid GOOSE messaging along for rapid modes of operation, islanding, and reconfiguration of the plant to match campus loads to the generation. All these logical connections were defined in the SCD file. However, given the brownfield nature, the configuration also had to incorporate a fallback mode. Essentially, the new IED configurations included two sets of logic: one that mirrored the pre-upgrade (hard-wired) scheme and one for the new scheme. During the transition, the old scheme remained active while the new IEDs were monitoring. The new IEDs were programmed to operate identically to the legacy hard-wired schemes until the final cutover, at which point a simple setting group change or remote signal would activate the new scheme fully.

FAT Execution: Given the complexity, a very extensive FAT was performed in a staged manner. All new relays, control IEDs, the HMI, and a new plant PLC were set up in a test environment mimicking the entire campus electrical network. Real-time digital simulators were used to emulate the power system: voltages, currents, and frequency changes during scenarios like utility outages and generator trips were injected into the relays. The FAT spanned several weeks and involved plant operators and engineers. Key aspects tested included:

- **Islanding Scenario:** Simulate the loss of the utility supply. The expected response was that the new system would open the main tie breaker, send run-up commands to generators, and adjust load via shedding if needed. During FAT, this sequence was verified step-by-step: the tie opened within cycles of the simulated fault, generator governors (in simulation) received the raise commands, and non-critical feeder relays dropped load according to the priority settings. All of this happened via GOOSE and was confirmed via event logs.
- **Resynchronization:** Once the simulated utility fault cleared, the system was supposed to resynchronize the campus to the grid. The FAT tested the logic that checked when the utility and campus were in phase and then issued a close command to the tie breaker. This was a delicate control involving a synchroscope; the test confirmed the new PLC and relays coordinated correctly, closing the breaker at the right moment and transferring load back smoothly.
- **Failover of Communications:** The network was set up with redundancy (PRP in this case). The testers introduced network faults (disconnecting one of the dual LAN connections in various places) to ensure that none of the GOOSE messages or control commands were lost or delayed. Indeed, the system showed resilience – even with one path down, operations continued uninterrupted, validating the redundancy design.
- **Legacy Integration Tests:** Portions of the FAT were dedicated to ensuring the old and new systems could coexist. For example, with the old system still “in charge” (pre-cutover mode), they simulated a load shed event and observed that the new system correctly logged it and that no unintended action was taken by the new IEDs. This proved that the new installation would not interfere with the running plant. Then, tests were repeated with the new scheme active (as if after cutover) to ensure it would then assume control properly.
- **Operator Drills:** The FAT environment allowed the campus operators to practice on the new HMI. They walked through routine operations (like transferring loads between transformers) and emergency procedures (like black start recovery) using the new interface. This familiarized them with the system and also helped identify any missing indications or controls that needed to be added before field deployment.

Outcome: The project proceeded to on-site implementation in phases, aligning with scheduled outages for each of the eight switchgear sections. Thanks to the preparation, each cutover went smoothly: the new equipment was installed and tested in the field largely following the procedure proven at FAT. When the time came to fully switch to the new IEC 61850 scheme, it performed as expected. In subsequent real events after project completion, the campus microgrid successfully handled utility disturbances with no loss of power to the campus, whereas prior to the upgrade such events would have forced an islanding with partial load shedding and generator trips. The new system automatically islanded the campus from the faulted utility line and then later resynchronized back, all without operator intervention, validating the efficacy of the design. This brownfield case underscores how exhaustive programming and FAT efforts paid off by delivering a resilient and optimized control system that met the high reliability needs of a critical facility.

LESSONS LEARNED

Integrating IEC 61850 in turnkey projects has yielded several key lessons learned, especially regarding testing and project delivery strategy. A consistent theme is that thorough upfront testing and planning are critical to avoid costly issues later. The following insights have been gathered from multiple projects (with client specifics removed for confidentiality):

- **Make FAT a Gate in the Project Schedule:** Treat the successful completion of a comprehensive Factory Acceptance Test as a major project milestone, rather than rushing to deliver equipment to site. Work that can be completed and verified in the factory will dramatically decrease overall project time and cost while improving the quality of the final product. In practice, tying deliverables (and payments) to a completed FAT ensures accountability for resolving issues early.
- **Develop Protection Settings Early:** Begin developing and testing relay logic, communication configurations, and network settings as early as possible. Final operational setpoints might be adjusted later, but the core logic and communications should be validated well in advance. Front-loading this engineering effort allows more time to troubleshoot and fine-tune the system in a lab or FAT environment, where problems are cheaper and easier to fix than in the field.
- **Simulate Real-World Conditions:** No matter how confident a team is in the design, nothing replaces testing the system in conditions that are as real as possible. Building a realistic simulation (with actual devices, network hardware, and software in the loop) will reveal integration issues or unexpected device behaviors that paper studies might miss. This approach is essential for catching hidden problems in IEC 61850 communications, timing, and interoperability before they can impact the live system.
- **Anticipate a Learning Curve:** If an organization is attempting their first IEC 61850 project, expect the process to be more challenging and time-consuming than traditional projects. Extra time should be allotted for engineering, FAT, troubleshooting, and commissioning activities. Each step will involve learning and adjustments to iron out unforeseen “kinks” in configuration, messaging, and device interactions. Future projects will go smoother as experience grows, but the initial project needs scheduled flexibility to accommodate this learning curve.

Consequences of Inadequate FAT – Real Examples:

Several projects have illustrated how skipping **or** limiting the FAT can lead to significant time and cost overruns:

- **Substation Integration Delays:** In one substation project, the team conducted only a basic functionality test in the factory instead of a full systems FAT. The control enclosure was delivered to site but remained inactive for months because many issues had not been worked out in advance. The lack of thorough testing led to insufficient resources on site and missed operational deadlines. The project incurred significant cost overruns due to extended on-site testing and multiple return visits by engineers, and it missed multiple scheduled outage windows, significantly extending the overall timeline.

- **Field Rework and Cost Overruns:** In another case, a substation upgrade relied on wiring interconnections in the field with minimal factory testing. Once installation began, numerous wiring and logic errors surfaced, forcing extensive troubleshooting. The time to complete the interconnects was much longer than planned, and the project price escalated due to nearly double the labor and rework costs required to fix issues on site. Ultimately the schedule slipped by an additional 4–5 months to accommodate the re-testing and modifications needed to get the system working.
- **Network Design Failure**: A large-scale substation overhaul skipped a full hardware FAT, opting instead for limited lab simulations without the complete set of devices. Unfortunately, the installed network could not handle the actual traffic and loading when the system went live, leading to cascading communication failures. This oversight necessitated a major redesign of the network architecture and protection scheme after installation on site. The corrective work caused substantial budget overruns and the delayed rework meant the project could not meet its intended energization date.

In each of these scenarios, the cost of inadequate FAT was significant: schedule slips, emergency design fixes, and even compromised system reliability in initial operation. The clear lesson learned is that a comprehensive FAT, involving all system components and as realistic conditions as possible, is not a luxury but a necessity for complex IEC 61850 projects. Stakeholders must allocate sufficient time and resources for FAT in project planning. Cutting FAT may save a little time upfront, but risks incurring far greater delays and expenses later. As a best practice, even if a full integrative FAT is not feasible, a simulated or partial FAT should be designed to cover all critical functions – for instance, testing at least the communication and logic using a subset of devices or a testing platform.

BALANCING FAT THOROUGHNESS WITH PROJECT CONSTRAINTS

While the benefits of an extensive FAT are clear, project managers often face constraints such as tight timelines, budget limits, and resource availability that can make a prolonged FAT challenging. It's important to balance FAT thoroughness with practical constraints, ensuring critical tests are not skipped even if some lower-risk areas are streamlined. Key considerations in balancing FAT depth include:

- **Cost vs. Risk:** A comprehensive FAT requires investment – time in a lab, equipment shipping or duplication, and personnel hours. Project teams should perform a risk assessment: identify which parts of the system, if untested, pose the greatest risk to success. High-risk, high-impact functions (e.g. protection coordination, inter-device tripping, any novel application) deserve full FAT attention. Lower-risk items (perhaps standard alarm mappings or minor sensors) might be verified with less exhaustive means. The cost of FAT should be weighed against the potential cost of failure. In a critical infrastructure project, the cost of an outage or major delay will vastly outweigh FAT expenses, justifying a thorough approach.
- **Time and Scheduling:** FAT can potentially delay the project if not planned well. To mitigate this, integrate FAT into the project schedule as a non-negotiable milestone rather than an afterthought. Some strategies to reduce schedule impact include starting FAT in parallel with certain site activities (if there is independent work) or dividing FAT into segments that allow some equipment to be released earlier. Additionally, ensuring that all engineering deliverables (schemes, configurations) are ready before FAT begins is crucial; otherwise FAT time might be wasted troubleshooting design issues that should have been resolved in the design phase.
- **Resource Allocation:** An intensive FAT may require a dedicated space and test equipment (e.g., power system simulators, extra test sets, networking tools) as well as specialized personnel (protection engineers, SCADA engineers, network specialists). Projects should plan for these resources. In some cases, engaging a third-party laboratory or a vendor's testing facility (as in the greenfield case study) can provide the necessary setup efficiently. If project resources are lean,

prioritizing the most critical tests and perhaps simulating the rest is a way to balance – but one should document clearly which aspects were not fully tested and have a contingency plan to test them carefully during commissioning.

- **Avoiding Over-Testing:** On the flip side, it is possible to over-engineer the FAT by trying to test every conceivable scenario, which could lead to diminishing returns. Aim for a representative set of test cases that cover all fundamental operations and a range of edge cases, but avoid an unbounded test scope, that does little to prove system operation and reliability.
- **Iterative Testing and Feedback:** Incorporate an iterative approach where findings from FAT are fed back into design improvements, and then testing is repeated on those points. Rather than striving for perfection in one giant round of FAT, it may be more practical to have two shorter FAT sessions: one to uncover any major issues, then a break to fix and refine, and a second round to validate the fixes and finalize. This can actually save time if scheduled smartly, as fixes can be done while some equipment is being installed or other work continues.

Ultimately, the key is striking a balance – ensuring that FAT is thorough enough to catch the critical issues (especially those that could jeopardize safety or reliability), while not so overextended that it derails the project schedule or budget. Effective planning, risk-based prioritization, and involvement of the right expertise are tools to achieve this balance. In the context of IEC 61850, given its complexity, leaning towards more testing is generally wise, but with a focus on quality rather than sheer quantity of tests.

POST-FAT: FROM FACTORY TO FIELD DEPLOYMENT

Once a system has passed Factory Acceptance Testing, the project transitions to preparing for shipment, installation, and on-site commissioning (the focus of Part 3 of this series). Several important steps should be taken post-FAT to ensure that the success in the factory translates to success in the field:

- **Incorporate FAT Findings:** Any changes or corrections identified during FAT must be updated in all project documentation. This includes revision of configuration files (SCD/CIDs), schematic drawings, logic diagrams, and operation manuals. It’s critical to maintain configuration control – the versions of settings and files that were tested and approved in FAT should be clearly marked as the versions to be used for deployment. If any temporary settings were used during FAT (for example, test modes or elevated thresholds for simulation), they should be returned to normal values before release.
- **Finalize System Documentation:** A complete set of documentation – including the final SCD file, settings for each IED, network configurations, and the FAT procedures/results – should be compiled. This serves as the reference for site engineers and also for future maintenance. The FAT report, in particular, can be useful on site to remind the team of any special instructions or known quirks discovered in testing.
- **Training and Knowledge Transfer:** Often the FAT is a prime opportunity for training, but additional training might be warranted after FAT. The team that will commission and operate the system should fully understand the configurations and how to interact with the system. Handoff meetings or training sessions can be held to walk through the system one more time, now with the benefit of the FAT experience. This ensures that the on-site personnel are not seeing the system for the first time in the field.
- **Deployment Planning:** Logistically, moving from lab to site can be a complex task. Every device that was tested in the lab needs to be installed in the correct location on site. A deployment plan or installation sequencing document should align with what was proven at FAT. For example, if the FAT was done with all devices connected, the plan might specify installing all those devices together in a new cabinet that can be hooked up in one go. In brownfield scenarios, the deployment

plan must integrate with outage schedules – often a stepwise plan (tested in FAT as well, as seen in the microgrid case) is executed: e.g., commission section by section, verify that section in the field (perhaps with a mini-FAT or SAT – Site Acceptance Test), then proceed to the next.

- **Site Acceptance Testing (SAT):** Although outside the scope of this part, it's worth noting that after installation, a Site Acceptance Test typically repeats critical tests from FAT to ensure nothing was disturbed during transport and installation. For instance, once wiring to actual field devices (CTs, VTs, breakers) is connected, a subset of tests (such as primary injections or functional trip tests) will confirm the system still behaves as expected. Since a full FAT was done, the SAT should have no surprises – it mostly verifies installation integrity.
- **Go-Live and Monitoring:** The ultimate deployment ends with the system going live. Initial operation should be closely monitored. Many teams leave certain test instrumentation or higher logging levels active for the first days or weeks of operation to catch any anomalies (for example, using network monitors to watch GOOSE traffic or enabling advanced event logging in relays). If any issue arises, the team can compare it against FAT results to diagnose if something different is happening in the real environment. Additionally, a plan for support (who to call if something fails) is set up, often with the integrator on standby during initial energization.

By following through on these post-FAT steps, the project ensures that the extensive work done in the factory isn't lost in translation. It creates a clear path to on-site commissioning, which is the final proving ground for the IEC 61850 system. With the programming validated and the system behavior vetted in FAT, the site work becomes more about physical installation and final checks, greatly reducing stress and uncertainty.

CONCLUSION AND FUTURE OUTLOOK

In conclusion, *Part 2: Programming and FAT* has highlighted the indispensable role of thorough configuration and testing in the success of turnkey IEC 61850 projects. The technical insights provided – from effectively using IEC 61850 configuration files to integrating multi-vendor devices, and from conducting exhaustive FAT procedures to managing greenfield vs. brownfield nuances – all underscore a central message: *meticulous preparation yields resilient, high-performance systems*. By investing effort in programming every device correctly and validating the entire system in a factory setting, project teams can significantly mitigate risks, avoid last-minute surprises, and ensure a smoother commissioning process.

The case studies of a new substation and a complex campus microgrid demonstrated how these principles apply in practice. In both scenarios, upfront engineering combined with thorough FAT led to outcomes where the systems not only met their design goals but were deployed with minimal rework and downtime. Importantly, the brownfield case showed that even in very challenging conditions (upgrading a live critical facility), IEC 61850's capabilities, when paired with careful planning and testing, enabled a successful transition with improved operational performance. Conversely, examining projects with inadequate FAT reinforced why skipping proper testing is a gamble no modern project should take.

As the industry continues to adopt IEC 61850 and digitalize substations, the processes of configuration management and integrated testing will become even more crucial. Trends such as increasing device complexity, stricter cyber-security requirements, and the advent of process bus (sending sampled analog values over the network) mean that future FATs may need to be even more elaborate, possibly using digital twins or advanced simulation to cover all aspects. Fortunately, tools and practices are evolving – standardized test procedures, improved vendor conformance, and automated testing solutions are emerging to support this need.

Looking ahead to *Part 3 of "Unlocking Turnkey IEC 61850 Projects,"* the focus will move to on-site testing and commissioning. There, the lessons from FAT are carried into the field, and the final verification of the system with live equipment and real power system conditions takes place. Part 3 will discuss strategies for site commissioning, including installation testing, protection scheme validation in situ, and cutover techniques, building on the groundwork laid by the engineering and FAT phases. Together, these parts of the series provide a comprehensive roadmap for utilities and engineers aiming to fully realize the benefits of IEC 61850 – from concept and design (Part 1) through configuration and factory testing (Part 2), and finally to on-site implementation and operation (Part 3).

Through this journey, one constant emerges: attention to detail at each stage is key to unlocking a successful turnkey IEC 61850 project. By maintaining a high standard in programming and FAT, practitioners set the stage for robust, future-proof substation automation that delivers on the promise of smarter, more reliable power systems.

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BIOGRAPHY

Ryan M. Bolduc, PE created, and heads Wunderlich-Malec’s business unit dedicated to the design, programming, testing and commissioning of Relay Protection & Control (P&C) Systems. The business unit specializes in advanced P&C upgrades, generator protection, islanding and synchronizing controls, in addition to generator plant/substation commissioning. His team has performed multiple turnkey IEC 61850 projects; while commissioning dozens of IEC 61850 projects in both power plant and utility substations. He is the engineer of record for the IEC 61850 Micro-Grid at the University of Massachusetts Medical School in Worcester, MA from initial conception to final commissioning. Ryan completed his first turnkey IEC 61850 project in 2013 for the electrical utility of Panama (ETESA), the first ever in the country.

Ryan attended the University of Maine where he received a BS in Electrical Engineering and a minor in Business.