

## Novel IEC 61850-based off-site engineering and validation methodology for protection, automation, and control systems

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### ABSTRACT

The IEC 61850 standard has driven the development of power systems Protection, Automation, and Control Systems (PACS) over the past years. Although it is well-known for its communication protocols, several concepts and features are underused. This paper presents a new engineering and validation methodology applying the IEC61850 standards concepts to optimize the project life cycle by standardizing and enhancing engineering and testing. An electrical specification has been defined according to the IEC 61850 data modeling, reducing misinterpretations at the specification and configuration stage. The proposed top-down configuration approach establishes a user's profile and product naming to eliminate the vendor's dependability. The validations were performed using modern commercial tools. The results show that the proposed methodology makes it possible to have a reliable engineering process where the output of the previous stage provides all required information is independent of the next one. The project naming approach makes it possible to validate the system integration based on the agnostic system specification files in an early project stage. Thus, the protection devices and supervision systems can be validated independently, reducing integration issues in the later stages without affecting interoperability and making it possible to achieve interchangeability.

### 1. Introduction

The IEC 61850 standard has been pushing the development of power systems Protection, Automation and Control Systems (PACS) towards the smart grid of the future, mainly in terms of communication protocols [1–4]. However, the IEC 61850 is much more than communication protocols [5,6]. In fact, over the past years, other aspects of the standard have been gaining notoriety [7–9] — for example, the top-down engineering process and application profiles [10,11]. Even though several concepts and features can improve the PACS implementation, they are still underused or not yet used at all [12].

Pursuing the IEC 61850 standard's usage has motivated research worldwide to do so effectively. In [11], the authors demonstrate an optimized IEC 61850 engineering process, highlighting the advantages of a top-down engineering approach. However, the proposed approach requires adding an interoperability tool during the design phase. In [13], the authors present an advanced tutorial about the IEC

61850 engineering process, but their work is based on the classical bottom-up approach. In [14], the authors present the technical aspects and requirements for testing station layers in smart grids, but no testing methodology is proposed.

The non-utilization of IEC 61850 standard features at the engineering and validation stages creates issues throughout the entire life cycle of a PACS project. These problems often manifest in system integration issues, engineering modifications, and increased complexity resulting from poor engineering and validation practices. Consequently, this led to delays in project delivery and increased costs. So far, there has yet to be an official definition of what can be called an IEC 61850 electrical design diagram, and there is no standardized method for testing IEC 61850-based systems. Nevertheless, international standards and guidelines like IEC 61850-10-3 and IEEE C37.233 can be used as foundations to create standardized methodologies [15].

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This paper presents an engineering and validation methodology to enhance project engineering and implementation process by employing the IEC 61850 standard concepts in engineering documentation. In addition, the proposed methodology includes the creation of an off-site configuration validation stage using modern IEC 61850 validation tools, which can validate the system configuration before proceeding with Factory and Site Acceptance Tests (FAT and SAT, respectively).

The paper's contribution can be summarized as follows:

- Developed a unified approach to Engineer and validate off-site a Substation Automation System (SAS) under The IEC 61850 standard;
- Each part of the approach presented is archivable and can be tracked for changes, providing a road map for the Engineering process in a formal and open form;
- The presented approach will reduce the FAT and SAT times and downsize equipment and workforce costs.

## 2. Proposed engineering and validation methodology

The proposed methodology for engineering and validation of protection, automation, and control systems has been created based on the actual project execution process of the Schneider Electric department called Digital Power Application Center (DPAC), which is responsible for PACS project execution. However, as presented here, the proposed methodology is general and easily applied to any project related to PACS. It is also worth mentioning that the selected project process follows the guidelines of the international standard for project management, the so-called Project Management Body of Knowledge (PMBOK®).

The proposed methodology consists of three main stages (explained in the following subsections):

- Stage 1: System Design and Specification. During the initial stage, the IEC 61850 abstract function models and standardized semantics are used in the engineering documentation in addition to the conventional electrical design based on ANSI/IEEE function numbers.
- Stage 2: System configuration. The system configuration is a top-down process, where the electrical specification diagram is imported into the engineering tool and converted into a machine-readable specification according to the IEC 61850-6 [16]. The system configuration is based on a completely agnostic approach using a customized application profile. Unlike the classic top-down approach, the proposed approach does not rely on the vendors' capabilities file, allowing the SCADA validation to proceed regardless of the Intelligent Electronic Device (IED) definition.
- Stage 3: System Verification and Validation. A separate verification and validation stage is designed for the SCADA and protection system to optimize and reduce system integration issues. The validation scheme is based on the Test Unit concept defined at the IEC 61850-10-3 and uses modern state-of-the-art validation tools. As a result, a new reliable testing method has been developed where the functional requirements can be thoroughly validated, and which can ensure true plug-and-play integration.

### 2.1. Stage 1: System design and specification

The IEC 61850 standards define functions and device model requirements for power utilities PACS. These definitions are enablers towards a standardized project design and specification under concepts understandable for the stakeholders involved. The system design is project documentation where the functional requirements are defined from an electrical layout perspective, including equipment, protection, and control philosophy. The project system design comprises electrical design documentation and a machine-readable system specification, which are explained below.

**Table 1**

A limited example of IEEE C37.2 and IEC 61850-7-4 relationship.

Functionality	IEEE C37.2	IEC 61850-7-4
Circuit breaker	52	XCBR
Synchro-check	25	RSYN
Instantaneous overcurrent	50	PTOC
Breaker failure	50BF	RBRF

**Table 2**

IEEE C37.2 and LN function relationship for the case of the distance protection.

Functionality	IEEE C37.2	LN function	LN class
Distance protection	21	PDIS	PDIS PSCH

#### 2.1.1. Electrical design

Today, there is no official definition in the standards about an IEC 61850 electrical design. However, it is common sense that an electrical design can be developed by using the definitions and guidelines provided by the standards. For instance, using the logical nodes (LN) classes defined in IEC 61850-part 7-4 joint to the well-known IEEE C37.2 device function numbers in the project engineering documentation. IEC 61850 Part 7-4 defines the LN classes as an aggregation of data objects that represent typical functions of the substation system. Table 1 shows illustrative examples of the relationship between the IEEE C37.2 device function numbers and IEC 61850-7-4 logical node classes.

However, the relationship between the IEEE and IEC standards is not always a one-to-one relation, as presented in Table 1. The IEC 61850 electrical design is not only about replacing one standard acronym for another; it is related to the art of making the electrical design fulfill the functionality. Thus, an excellent standard-based design shall also include the application function concept. An LN is the smallest part of an application function that exchanges data to fulfill its role [17]. The functional concept allows multiple LNs to be combined into groups to perform an application. IEC 61850 Part 5 defines the requirements for modeling application functions. Table 2 shows an illustrative example of a distance protection function described as IEEE C37.2, LN function, and LN class.

Fig. 1 presents an example of an infeed line bay electrical design template based on the IEC 61850. The template comprises a generic representation of the bay single-line diagram (right) and a functional specification (left). The purple squares represent bay equipment functions, where QX is Q3 (circuit breaker), QX1/QX2 refers to Q31 and Q32 (circuit switch), and QT is QT3 (earth switch). The square labeled IED defines all functions that shall be performed by the same IED. The red squares represent groups of LN classes associated with each piece of equipment to perform its function.

In addition, a well-designed IEC 61850 electrical design documentation should contain all the required information to start the IEC 61850 system specification and configuration. Therefore, to support the electrical design functional definitions presented in Fig. 1, the IEC 61850 design documentation should also include a document where the Piece of Information for Communication (PICOM) is represented and the data exchange between the functions can be specified, as well as the logic/functional behavior of the LNs. The PICOMs describe the exchanged data between two application functions or subfunctions. It represents where the data came from (source), where the data goes (sink), and what the data is (attribute). Fig. 2 presents an example of the logical architecture of a distance protection application function.

The boxes in Fig. 2 represent the LN classes, which are tagged based on the naming of IEC 61850 part 7-4. The small boxes within each LN class box denote the data objects defined in part 7-4, which are used for each class to perform the application function. The logical connection (LC) arrows represent the PICOMs, with the sending LN as the source and the receiving LN as the sink. The voltage transformer (TVTR) and the current transformers (TCTR) send the voltage (VolSv) and current

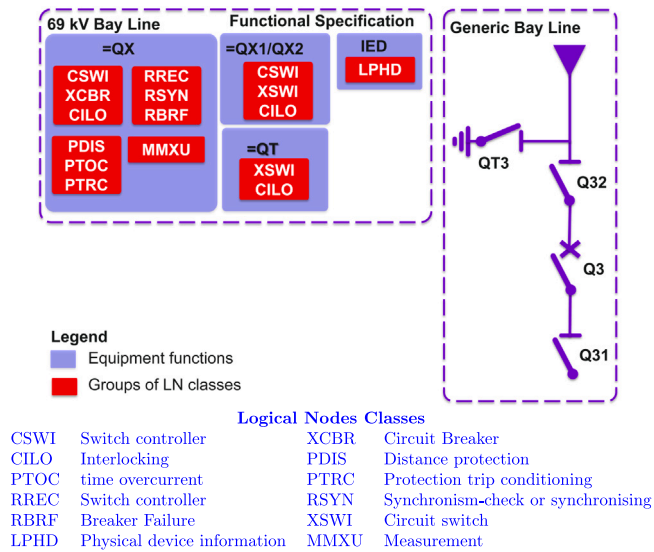


Fig. 1. Illustrative example of the IEC 61850 electrical design of generic infeed line bay, including functional specification (left) and single line diagram (right).

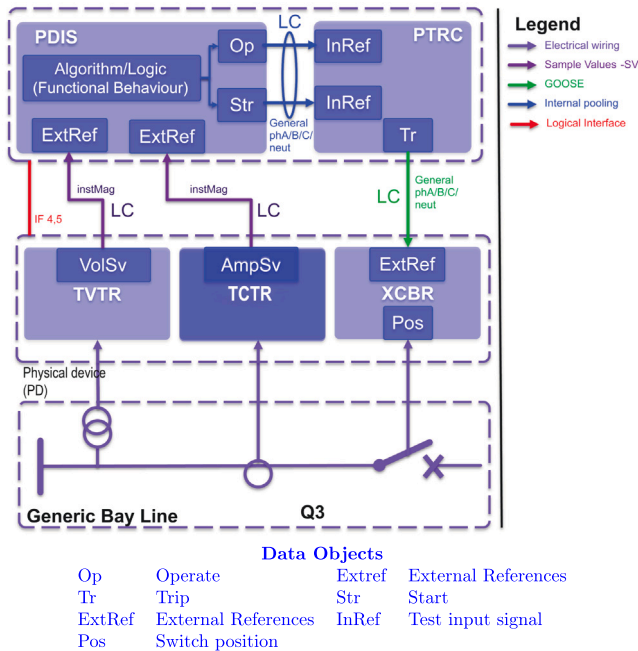


Fig. 2. Illustrative example of the logical architecture of a simple distance protection application function.

(AmpSv) instantaneous value as a magnitude data attribute (instMag) to the distance protection (PDIS) using sampled values indicated by the purple arrow.

The distance protection PDIS function sends protection start (Str) and operate (Op) signals to the trip conditioning function (PTRC) via internal polling (blue arrows) since both functions are hosted on the same physical device (PD). The PTRC sends the trip (Tr) order to the circuit breaker (XCBR) using the Generic Object-Oriented System Event (GOOSE), represented by the green arrow. The logical interfaces (IF 4,5) specify the type of connection based on the criticality of the exchanged data for each interface. The interface definition is used to identify the necessary performance requirements for each interface as per the IEC 61850-5.

These pieces of information are usually defined in the SCL files. However, defining the logical architecture later can be problematic as it may rely on a personal interpretation of the scheme. Furthermore, SCL is a machine-readable file in Extensible Markup Language (XML) format, which may be challenging for stakeholders unfamiliar with SCL files and configuration tools. Therefore, a human-readable document presenting the information in Figs. 1 and 2 is vital as an implementation guide for the system specification and configuration.

### 2.1.2. System specification

The IEC 61850 part 6 defines a common language called System Configuration Language (SCL). SCL provides a standardized machine-readable file format for configuring and setting communication parameters, communication system configurations, switchyard functions, and their relations in IED communication. The primary purpose of this format is to allow the exchange of IED capability descriptions and system descriptions between IED engineering tools and system engineering tools, regardless of the manufacturer. The SCL files have different purposes for data exchange and are therefore distinguished for the data exchange between tools by utilizing different file extensions. Nevertheless, the contents of each file shall obey the SCL rules defined in part 6. Table 3 presents the tools, extension, and purpose of each SCL description file type.

The system specification describes the system's logical and functional architecture using the SCL language. It describes the specification of the system at a single line/electrical process as well as the function's definition [18]. Part 6 of the IEC 61850 standard defines an SCL, which provides a syntax to be used by the engineering tools to create machine-readable IEC 61850 files. The System Specification Tool (SST) is used to create an SCL file that contains the electrical and functional design information to be used as a model and constraint for the system configuration; this file is called the System Specification Description (SSD). The SSD contains the description of the single-line diagram and functions of the substation represented by logical nodes. The logical nodes defined in an SSD are abstract, which means they are not assigned to a specific device. However, the abstract functions can be placed into virtual IEDs.

Fig. 3 illustrates the substation description and function allocation in an SSD file following the SCL schema. In ①, the substation section provides descriptions of the voltage levels. In ②, the feeder bay sections are presented under their respective voltage level section. In ③, the definition of a circuit breaker equipment within the bay section and the assignment of the electrical equipment to an abstract circuit breaker function located in a virtual IED are depicted. In ④, the definition of the Virtual IED is shown. It is noteworthy that as it is a virtual IED, neither the type nor the vendor is defined in the IED section.

Creating a virtual IED allows the user to build a more detailed system description. The ongoing development of the Technical Report IEC TR 61850-90-30 (that is planned to be incorporate in part 6 Edition 3) define an SCL extension that allows the generation of virtual IED files separately in an IED Specification Description (ISD) file extension.

### 2.2. Stage 2: System configuration

The system configuration is the stage where the abstract system is assigned to a specific vendor's IED capabilities description (ICD) to perform the functions according to the definition located in the SSD. The system configuration is commonplace in IEC 61850 projects regardless of the engineering approach used [11]. However, in the conventional engineering approach, also known as bottom-up, the configuration is the first and foremost step since the system is configured and modeled according to the devices that will be rather than configured and modeled according to a system specification.

The system configuration starting from a system specification dramatically reduces the work to be done in the configuration phase since all functional requirements will already be defined. Thus, the user will

**Table 3**  
IEC 61850 engineering tools and SCL files relation.

Engineering tool	SCL file	Extension	Purpose
System Specification Tool (SST)	System specification description	*.SSD	Data exchange between a system specification tool and system configurator, providing information on the substation's single line diagram, functions, and logical nodes. It requires a substation description section and may include data type templates and logical node type definitions.
	IED specification description	*.ISD	Provides a specification of capabilities required for a specific IED choice. Vendors are intended to be compared against ICTs to determine the degree of match.
System Configuration Tool (SCT)	System configuration description	*.SCD	Data exchange from the system configurator to IED configurators. This file contains all IEDs, including the configured data flow and needed DataTypeTemplates, a communication configuration section, and a substation description section.
	System exchange description	*.SED	Data exchange between system configurators of different projects. This file describes the interfaces of one project to be used by the other project and reimport the additionally engineered interface connections between the projects.
IED Configuration Tool (ICT)	IED capability description	*.ICD	Data exchange from the IED configurator to the system configurator. This file describes the functional and engineering capabilities of an IED type. It shall contain precisely one IED section for each type whose capabilities are described.
	Configured IED description	*.CID	Data exchange from the IED configurator only to the IED. It describes the communication-related part of an instantiated IED within a project.
	Instantiated IED description	*.IID	Data exchange from the IED configurator to the system configurator for a single IED preconfigured explicitly for a project, e.g., to include a preconfigured instance file or IED instance value changes or data model modifications.

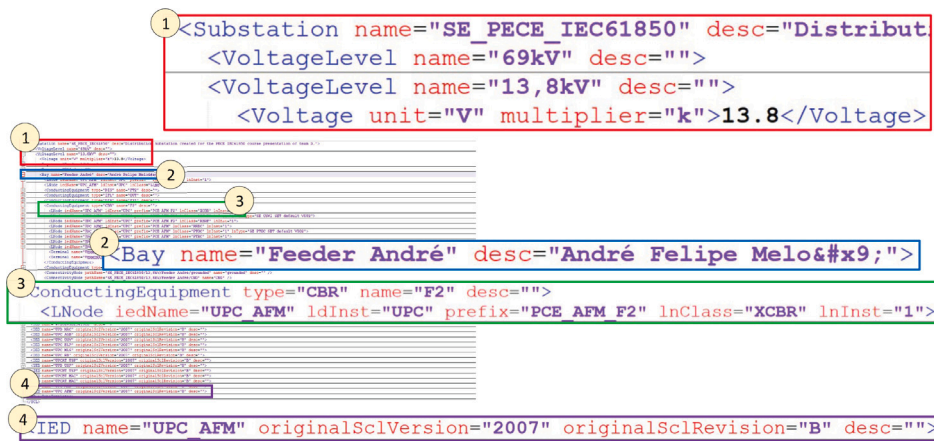


Fig. 3. System Specification Description XML breakdown.

only need to assign the vendor ICD files to the virtual IEDs to generate the System Configuration Description (SCD). At this stage, it is also possible to verify whether the chosen IED meets the specifications' requirements. This engineering approach is called Top-down. Fig. 4 presents the top-down configuration workflow starting from a system specification based in six steps described below:

- Step 1: The system specification tool (SST) creates an SSD file (1) where all system constraints are already defined.
- Step 2: The IED configuration tool (ICT) creates the ICD file (2), where the capabilities of the intended IED are described.
- Step 3: The system configuration tool (SCT) checks the ICD against the SSD constraints and generates the SCD file (3).
- Step 4: The ICT issues the CID file (4) for the IED.
- Step 5: The ICT updates the IED description based on the further IED configuration needs and system configuration needs provided by SCT in Step 3. The ICT exports the updated configuration description to the SCT via the IID file (n). (5).
- Step 6: The SCT publishes the updated SCD file that will be used for all systems and subsystem configuration tools involved (6).

The base data model within an IEC 61850 is referred to as Product Naming (PN), which the manufacturer predetermines according to the standard rules. PN serves as the IED's fixed or default data model,

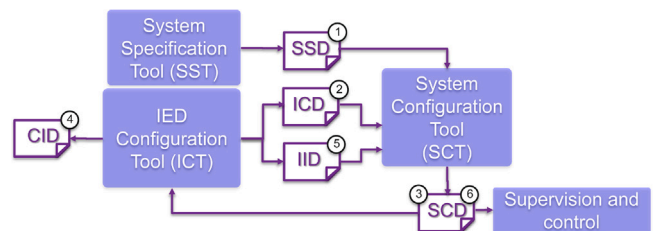


Fig. 4. Classic top-down workflow of the configuration process.

including the logical node naming that is composed of a prefix, LN class, and suffix (instance). PN reflects the IED's hierarchical structure and function content. The IEC 61850 standard defines the logical node classes, and it cannot be changed. However, the default definition of the logical node prefixes and instances can vary according to the manufacturer.

Flexible Product Naming (FPN) is a feature that enables users to create a custom naming profile for their application and modify the default IED data model. This modification consists of changing the logical node prefixes, instances, or both, following the user profile and the LN naming conventions set out in parts 7-2 of the standard.



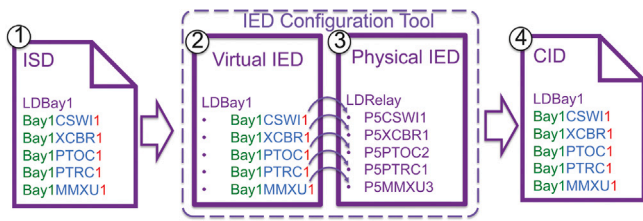


Fig. 5. An illustrative example of the Flexible Product Naming workflow.

Furthermore, FPN is the main enabler to achieving IED interchangeability since the used data configuration will be identical regardless of the manufacturer. Fig. 5 presents an example of an FPN configuration process presenting details of the workflow. The input of the workflow is the ISD file to the IED configuration tool to finally produce a CID. The FPN workflow shown in Fig. 5 consists of the following steps:

- Step 1: The ISD file ① configured with the customer naming profile is generated based on the project specification.
- Step 2: The ISD file is imported into the ICT (see ②).
- Step 3: The predefined data model receives the new prefix and instance from the reference ISD (see ③).
- Step 4: The ICT generates the new customized CID file (④) to configure the real IED.

Fig. 6 illustrates the configuration of an SCD file with FPN and dataflow in a configuration tool interface. In ①, following the assignment of the ICD file to the virtual IED, the type and manufacturer are specified in the IED section, defining the actual IED to be utilized in the application. In ②, the GOOSE subscriptions are detailed in the Inputs section, referring to the configured data reception by the IED. Each external reference (ExtRef) presents the service utilized in the data exchange, its data source, and destination. It is pertinent to note that the data prefix is customized due to the use of FPN, ensuring adherence to the specification. Finally, in ③, the Client/Server data flow is depicted, with the designation of a Client (HMI1) defined in the Report Control Block section.

2.3. Stage 3: System verification and validation

According to the IEC 61850 part 10-3 released in 2022, Substations Automation systems have the potential to be complex engineering solutions that require multiple levels of testing to verify and validate the components, architecture, and design against a set of requirements [15]. The project contract usually defines the verification and validation stages. The verification and validation process details can

vary according to several aspects, like national and international regulations, customer requirements, and even project management definitions. However, the point of common agreement is that in the project execution chain, the tests are divided into two types of acceptance tests: Factory Acceptance Tests (FAT) and Site Acceptance Tests (SAT).

The FAT is the first verification and validation stage in the project chain. Once the system configuration is delivered, the equipment is installed in a controlled environment (i.e., laboratory or factory), and a series of tests are performed to ensure that the system works according to its design specifications. The FAT is the first protection and supervision system integration validation in the conventional verification and validation approach. Moreover, the FAT assessment results are the prerequisite to proceed with the system to field installation and SAT. Thus, in the ideal scenario, all integration and functional issues shall be detected and solved at this stage.

The SAT is the latest stage before the final delivery of the project. When the system is installed on-site, a series of end-to-end tests are performed to verify that the entire scheme is working correctly. Since individual subsystems have already been validated in the factory, it is usually not necessary to re-run all test routines for each subsystem. However, in case of high systems or where previous FAT tests have been poor or absent, the commissioning shall require additional and/or repetitions of subsystems' individual testing. In addition, the proposed methodology introduces an intermediate verification and validation stage off-site previous to the FAT stage, where it is possible to ensure the expected behavior from the protection and control system before sending the devices and engineers to the factory and consequently eliminating the high cost of debugging the system in later stages where required high cost in people logistics and factory/site space allocation.

3. Application test case

Fig. 7 shows the flowchart of the proposed methodology and the system architecture used in the validation stage, whereas DUT means Device Under Test and SUT means System Under Test. In the first step, computer-aided design (CAD) software is used to create the system's electrical and functional design, using popular commercial software like Autodesk AutoCAD®, Microsoft Visio®, etc. Secondly, the machine-readable system specification and configuration, SST, and SCT could be created with a sort of commercial software available; in this application case, the authors decided to use EcoStruxure Power Automation System Engineering (EPAS-E). The IED is configured based on the ISD file and optionally using the FPN.

The client functional testing can be implemented using a combination of software and hardware. In this paper, OMICRON StationScout IEC 61850 is selected for that purpose. On the other hand, for the IED validation before the acceptance test (FAT, SAT), a test set with 61850 Client/Server is used. The authors used for the IED validation

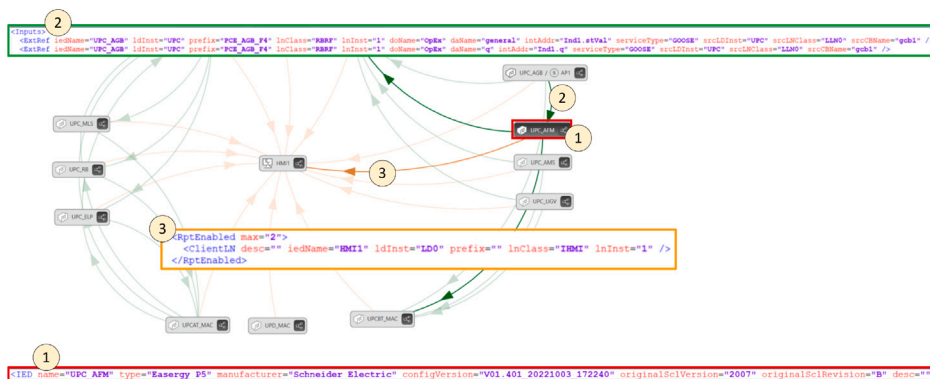


Fig. 6. System configuration description dataflow XML breakdown.

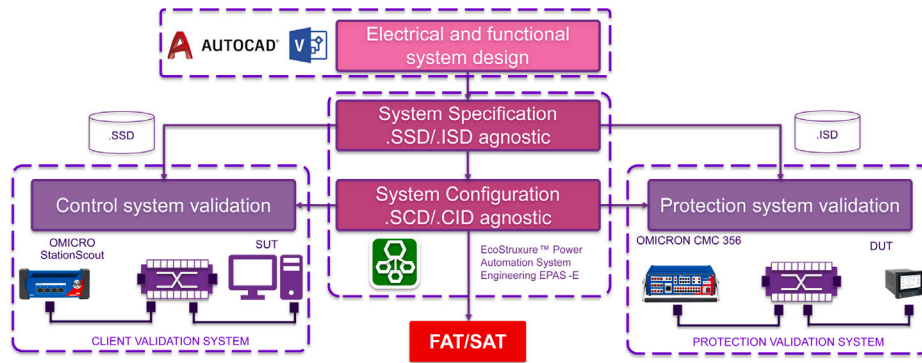


Fig. 7. Flowchart of the proposed engineering and validation methodology.



Fig. 8. Photo showing the laboratory setup used for the verification and validation stage.

an OMICRON CMC 356<sup>1</sup> equipped with the IEC 61850 Client/Server module (Fig. 8).

### 3.1. Stage 1: Project electrical specification

The proposed electrical specification consists of the creation of an electrical and logical project using the IEC 61850 part 7-x data modeling. The electrical design documentation defines the electrical wiring and single-line diagrams and the association with their respective functions using IEC 61850 semantics. Fig. 9 presents the benchmark document created for the electrical specification. The authors developed a single-line diagram of a classical distribution substation with three 69 kV bay lines, two 69/13.8 kV bay transformers, and four 13.8 kV bay feeders. In ①, the document presents an example of a classic single-line representation of an Infeed Bay Line. In ②, the document presents the required functions for each electrical element in the diagram according to its respective bay template. In ③, the document does an ANSI/IEC relationship legend to facilitate the understanding to Engineers who are not entirely familiar with the IEC 61850 nomenclature.

The IEC 61850-7-x defines the LN classes and their data objects (internal parameters). However, the standard does not define the logical behavior behind each LN. For this reason, to guarantee the complete functional specification, it is required to create a logical specification document where the functional behavior (logic) behind each LN is defined. Fig. 10 presents the defined logical specification for the CSWI. The figure is divided into four distinct parts to be detailed, which will be referred to as ①, ②, ③, and ④ for clarity and ease of description. In ①, the document shows the origin of the signals and their references,

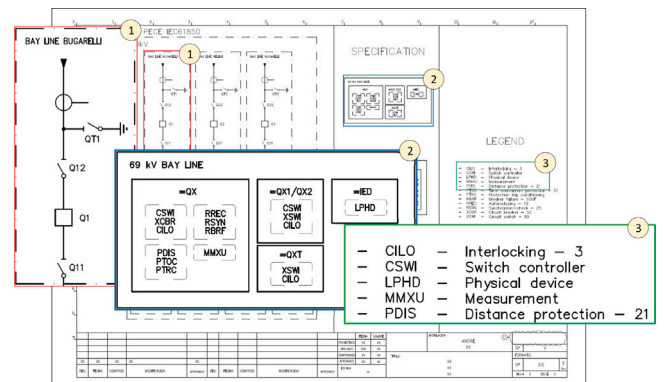


Fig. 9. Electrical design specification — IEC 61850 single line diagram.

meaning, tag in the document, and the page number. The middle section, numbers ②, and ③, shows the control logic using the classical IEC Boolean representation and the data model associated with the logic. The right side, number ④, defines the output of the logic and its respective data attribute in the LN. It can be seen that the proposed design guarantees that the output documentation of the project electrical specification stage contains all information required to start the system configuration stage, respecting the project’s functional constraints without any extra documentation or human interaction for further clarification.

### 3.2. Stage 2: System configuration

The system configuration stage begins importing the Single Line Diagram (SLD) into the SST. The authors used the EPAS-E Software as SST and SCT. Fig. 11 presents the top-down configuration approach used in the proposed methodology. The figure is divided into six distinct steps, labeled from ① to ⑥, for the purpose of detailed examination and clear

<sup>1</sup> The OMICRON CMC is a test tool used for secondary injection for testing protection relays and measurement devices (basically, it simulates the values as if it were the secondary side of a CT and VT). It has six current sources, four voltage outputs, ten multifunctional inputs, four binary outputs, a DC auxiliary supply, high accuracy, and an integrated network card for testing IEC 61850 devices. It is fully operating by using the Test Universe software.

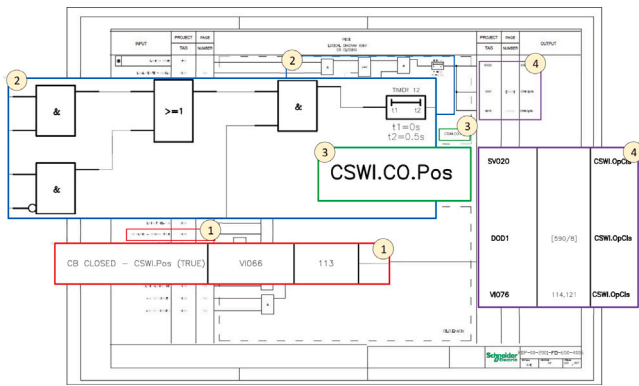


Fig. 10. Electrical design specification — IEC 61850 logical diagram.

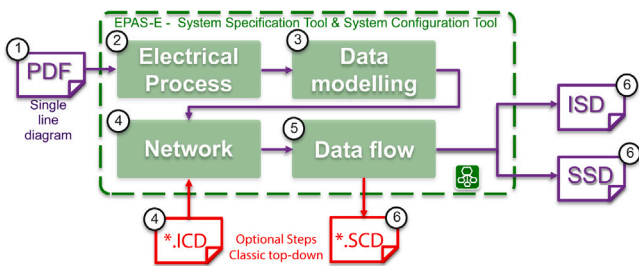


Fig. 11. EPAS-E top-down agnostic system configuration.

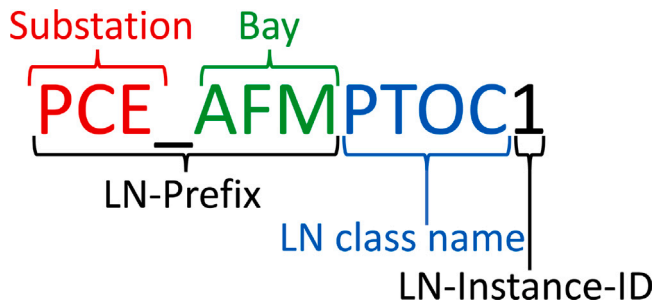


Fig. 12. Application LN naming specification.

description. The electrical design generated in the previous stage is represented in ①. In ②, the single line diagram is imported by EPAS-E and converted into a machine-readable electrical specification according to IEC 61850-6 SCL. In part ③, the data modeling is defined based on the electrical specification document, and the LN classes are assigned to their respective bays, equipment, and the corresponding virtual device that will host the function. To ensure the project standardization and interchangeability, the LN were configured according to the customer profile in terms of data (objects and attributes) and LN naming. The application LN name is defined according to Fig. 12. The LN prefix is composed of the substation and bay trigram. The LN class meaning is defined according to the IEC 61850-7-4. The instance ID is defined according to the number of instances required in the application.

The creation of an LN name according to the application instead of the used IED is the key factor to enable interchangeability. The vendor IED will adapt its data modeling according to the application by using FPN. The FPN allows the user to adjust the IED data modeling according to a defined customer profile using the ISD generated by the engineering tool. The system configuration stage also includes the network parameter configuration, ④, and the communication protocols data flow, including datasets report and GOOSE control blocks, as presented in ⑥ of Fig. 11. Since the configuration was based on an abstract approach, the engineering tool will generate an SSD file. However, it will contain the Dataflow configuration, unlike conventional SSD files.

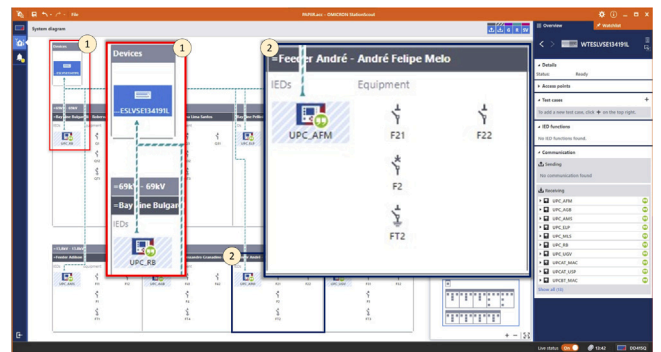


Fig. 13. Illustrative example of the system simulation using OMICRON Station Scout tool.

Unlike traditional engineering methodologies, the proposed methodology does not require any vendor-specific definition at the System configuration stage, and the SCADA system validation can be made even before the IED vendors' definitions. However, the proposed validation methodology is not useful only for the best possible (favorable) scenario since the proposed methodology can also be applied to a conventional engineering process. In this scenario, the vendor's ICD will be imported into the engineering tool prior to the protocol data flow configuration, and the engineering tool output will be a conventional SCD file, as presented in red ④ and ⑥ in Fig. 11.

### 3.3. Stage 3: System verification and validation

The proposed client validation stage consists of stand-alone testing of the supervision and control system prior to the FAT stage. The SCADA system is end-to-end tested using a TestSet hardware capable of simulating the whole Substation system and its IEC 61850 capabilities by importing the SCL file generated at the previous stage, as presented in Section 2.2, an SCD or SSD with defined dataflow. In addition, the proposed TestSet can generate a report for all test scenarios and its IEC 61850 signals that will be used to validate the test against the SCADA event log. For this configuration, an OMICRON MBX1, cybersecurity, and mobile digital substation analysis test set hardware could be used to read the SCL and create a substation setup with a graphical interface provided by the Station Scout software. Fig. 13 presents the Project SCL running in the TestSet. The figure is divided into two distinct parts, each labeled from ① to ② to ensure clarity and facilitate a better understanding, these figure sections have been enlarged, enabling improved visuals. In ①, the blue arrows represent the MMS data flow from the simulated IEDs to the SUT. The graphical view is automatically created based on the electrical information contained inside of the SCD/SSD according to IEC 61850-6 as presented in ②.

In addition, the test scenarios are created by copying the SCADA signal list table from the SCADA system database and pasting it into the test set interface. The Scada list is composed of the SCADA signal tag and related IEC 61850 data. The test set software uses the IEC 61850 data as a foreign key to cross the data and associate the SCADA tag to its respective simulated signal in the test scenarios report. Fig. 14 presents the simulation test report and the SCADA event log. Certain portions of the figure have been highlighted and magnified to enhance clarity and comprehension of the process, allowing for improved visibility and understanding. The blue mark shows a comparison of the same event presented in ①, the SCADA log, and ②, the test report. As can be seen, the proposed approach is more reliable than conventional software-based simulators running in a Windows environment. Besides the validation report, due to the dedicated hardware, test engineers do not need to worry about Operating Systems (OS) tasks and software that may impact the simulation, for example, WinPCAP and Firewall.



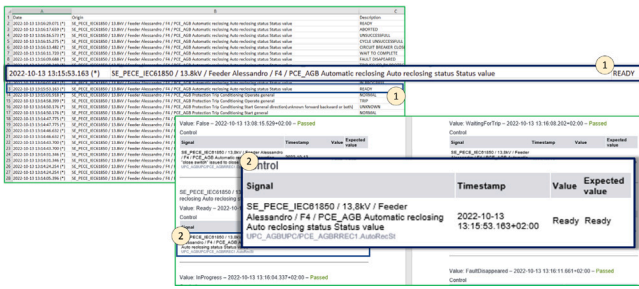


Fig. 14. Client validation report and system event log cross-checking.

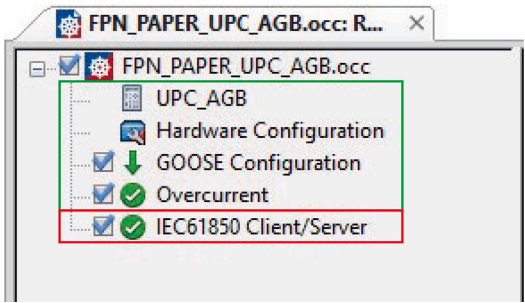


Fig. 15. Inclusion of the client-server module in the OCC test routine.

The protection validation stage is based on testing the protection IEDs so that it is possible to guarantee full configuration functionality using the concept of IEC 61850-10-3 Unit testing, not only in terms of protection but also in terms of logic and communication functions. In this work, a benchmark test set OMICRON CMC 356 was used for this test. The OMICRON Control Center (OCC) allows the creation of several test modules for different function tests. The proposed protection testing relies on including an IEC 61850 Client/Server test module in the OCC. The classical protection test modules remain the same in the test-routine file. Thus, after the validation of all protections, the test routine will run an additional IEC 61850 module that will validate the correct response of the IED in terms of communication. Fig. 15 shows the OCC File modules sequence for a Feeder Overcurrent protection validation. The green square mark shows the conventional

modules in a classical overcurrent validation. The red square presents the Client/Server module created for the proposed validation methodology.

The IEC 61850 Client/Server module consists of the creation of a sequence of different test scenarios. For each scenario, the signals sent to the DUT (analog, inputs, and control), the expected response, and the assessment criteria must be configured in the test set. Fig. 16 presents an example of a feeder overcurrent protection IEC 61850 Client/Server validation in a UML Sequence Diagram. The Set IED stage is the first sequence step, where the test set will enable the Report Control Blocks and set the Trigger Options. At the pre-fault stage, the test set will provide rated values for the DUT and assess the data values response and reason for inclusion. After that, the Fault stage, where the test set sends fault values and assesses the trip response signal and behavior.

The output of the protection validation stage is the full OCC test report, which will include all protection assessments and the final client/server results to guarantee correct system integration. Fig. 17 presents the most relevant data in the IEC 61850 client/server report results. The red square highlights the test header, including the DUT IP and SCL file. Regarding Fig. 17, the yellow box area shows the Set IED stage configuration, including the Report Control Block (RCB) and Trigger Options. The right blue boxes present the injected fault values and the dataset signals at the Fault A stage. The left bottom green boxes show the received response and assessment results. In addition, the test report signals Timestamp in each scenario, which can be used to cross-check against the DUT event log.

#### 4. Conclusions

This applied paper has introduced the development of a new engineering and validation methodology using the best IEC 61850 features and available commercial tools. A benchmark distribution substation has been used to validate the methodology, starting from the electrical design, system configuration, and finally, the decentralized protection and SCADA validation.

Section 3.1. has presented the final engineering documentation created using the IEC 61850 data modeling concept. The delivered electrical design diagram defines the electrical functional requirements by assigning the IEC 61850 LN classes and doing their respective association with the ANSI/IEEE Function Numbers. In addition, the logical diagram specifies the logic behavior behind each function that

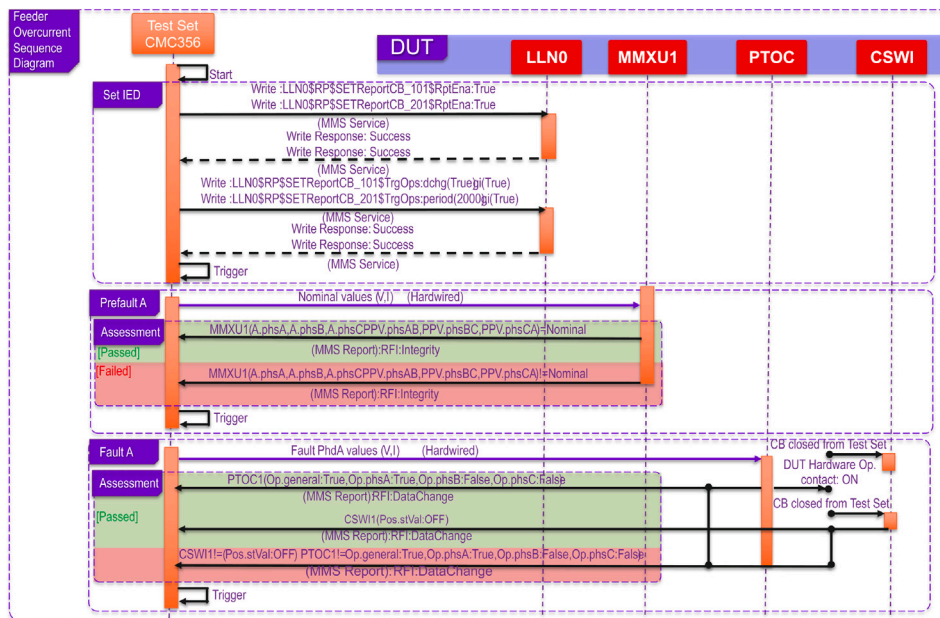


Fig. 16. UML Sequence Diagram for an overcurrent test scenario.



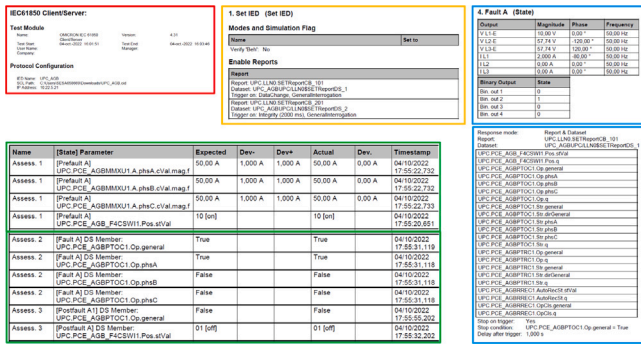


Fig. 17. IEC 61850 client-server module test report.

will be used to guide the device’s configuration and validation. Thus, the delivered documentation contains all required data for the correct system configuration without any additional documentation.

The system configuration is presented in Section 3.3, shows a complete vendor-agnostic system configuration. Unlike the classic top-down approach, the vendor ICD file was not mandatory to proceed to the data flow configuration. The proposed method configures the protocol data flow using virtual IEDs with customized application profiles. Since the LN name and data profile are application-defined regardless of the IED vendor, after the configuration, the engineering tool generates an ISD file used to customize the LN naming on the select IED using the FPN feature. This approach is the key aspect to achieving interchangeability. In addition, the engineering tool creates an SSD file for the SCADA configuration. However, the generated SSD contains the network and data flow configuration, making the SCADA configuration and validation possible regardless of the IED vendors’ selection.

Section 3.2 have presented the proposed validation and verification methodology results. Unlike traditional manually filled validation spreadsheets, the use of a modern simulation tool enables full SCADA validation. It generates a detailed test report that joins the system event log, making the validation auditable even in later phases of the project. Including communication validation into the protection routine ensures the right communication configuration at the Protection IED and consequently, dramatically reduces possible system integration issues in the FAT and SAT stages. To summarize, the proposed methodology presented in this paper reduces the systems integration and configuration problems from the early stages of the projects, reducing FAT and SAT times and decreasing the project TOTEX (Capital Expenditure + Operational Expenditure). In addition, the proposed validation methodology and electrical design specification are not strictly tied to the proposed system configuration methodology. It can also be applied to classic top-down and bottom-up system configurations.

**CRedit authorship contribution statement**

**André Felipe Silva Melo:** Writing – original draft, Resources, Methodology, Formal analysis, Data curation. **Juan Manuel Roldan-Fernandez:** Writing – review & editing, Visualization, Conceptualization. **Francisco Gonzalez-Longatt:** Writing – review & editing, Visualization, Conceptualization. **Manuel Burgos-Payan:** Writing – review & editing, Visualization, Conceptualization. **Ulisses Chemin Netto:** Writing – review & editing, Visualization, Conceptualization.

**Declaration of competing interest**

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: ANDRE FELIPE SILVA MELO reports administrative support and equipment, drugs, or supplies were provided by Schneider Electric Spain. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Data availability**

Data will be made available on request.

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