

SysGrid: IEC 61850/IEC 61499 Based Engineering Process for Smart Grid Automation Design

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Abstract — The paper proposes a novel computer-aided model-based system engineering process for Smart Grid applications. The process is supported by the SysGrid tool that plays the roles of system configurator and device configurator. The design process starts with single line diagrams which are automatically transformed to executable function block specifications. The process is based on the Smart Grid control architecture that is a heterogeneous network of controllers communicating in a peer to peer manner. This "artificial nervous system" of the Smart Grid will be capable of self-healing and dynamic adaptation to renewable generation and ever-changing loads. The tool supports system-level design of automation logic in the form of function block networks with compliancy to IEC 61499. The capabilities of SysGrid are demonstrated through the process of designing a distributed protection application.

Keywords-component; IEC 61850, IEC 61499, SysGrid, Function Blocks, SCL, Intelligent Logical Node, Co-Simulation, Model-Based System Engineering

I. INTRODUCTION

The Smart Grid in the broad sense is understood to be the future power generation, transmission, distribution and consumption infrastructure enabled by advanced information, communication and control technologies. The Smart Grid evolves into a large, complex and interconnected system of systems, incorporating such components as distributed generation, energy storage systems, smart loads, new generation, solid state transformers and fault isolation devices. The Smart Grid is expected to evolve to a level where traditional engineering techniques will be challenged by the complexity of system requirements [1], for designing and testing Smart Grid applications.

This paper introduces Model Based Systems Engineering (MBSE) methodology for Smart Grid automation that encourages formal and consistent specification and design. The design flow follows the IEC 61850 standard [2], and results in distributed software in IEC 61499 architecture [3]. The methodology relies on validation and testing of the application via co-simulation. The proposed methodology is realised by the authors in a tool prototype called "SysGrid".

According to [4], there are three elements in a MBSE environment: the modelling language, the modelling tool and the modelling process. Table 1 presents the three elements of MBSE mapped to the architecture of the proposed SysGrid tool. The modelling languages used are IEC 61850 and IEC 61499. The modelling tool is SysGrid and finally, the modelling process is adopted from both the IEC 61850 and IEC 61499 standards.

Table 1. Elements of SysGrid MBSE environment.

MBSE elements	Proposed process
Modeling language	IEC 61850 & IEC 61499
Modeling tool	SysGrid
Modeling process	IEC 61850 & IEC 61499

The paper is structured as follows. Chapter II is a short survey of the state of the art of related. Chapter III outlines the motivation for this work. Chapter IV introduces the design process of the MBSE solution. Chapter V outlines the architecture and the main features of SysGrid. Chapter VI shows a case study of a distributed protection application developed using the SysGrid and Chapter VII concludes the paper with summary and future work.

II. STATE OF THE ART

Currently, there is no single standard that embodies all aspects of a Smart Grid system engineering in a unified format to provide interoperability allowing different layers of Smart Grids to interact with one and other. Smart Grid Architectural Model (SGAM) is a reference Smart Grid architecture designed for the European market developed by the CEN-CENELEC-ETSI Smart Grid Coordination Group [5]. SGAM provides a pathway for transforming Smart Grid use cases to the SGAM architecture. However, the transformation SGAM model is not presented in a formal format which could be used further to for example, to generate control models.

Two standards which do present formal models and description of certain parts of a Smart Grid are the substation

automation standards IEC 61850 and IEC 61970 – part of the Common Information Model (CIM) collection which includes IEC 61968. The scope of IEC 61850 ranges from information modeling of functions and equipment to how the information is exchanged on the device level. IEC 61970 is purely an information model which defines semantic models of power system components and the relationships between the said models. CIM models provide a higher level of abstraction compared to IEC 61850 since the models in IEC 61850 are largely functional. CIM is developed in UML centered on inheritance while the information model of IEC 61850 is largely hierarchical with multiple levels of information encapsulation in each model. The goal of IEC 61970 is to facilitate the exchange of network data between companies and applications with a unified information model, creating an interoperable solution between IEC61970 and IEC 61968 with common canonical models. Interoperability is also a feature of IEC 61850 in the form of the System Configuration Language (SCL). However, interoperability in IEC 61850 only exists between IEC 61850 applications. There are ongoing works harmonizing the two standards incorporating CIM information models to IEC 61850 to take advantage of the interoperability and the communication features [6, 7] offered by IEC 61850. IEC 61850 was chosen at this stage over CIM since IEC 61850 provides the information model and the communication configuration backbone which are lacking in CIM even though CIM provides a higher level of model abstraction.

What is currently not available in IEC 61850 however is a formal description of the logic of the function itself in each logical node. This missing void could be filled by either IEC 61131-3 or IEC 61499, although IEC 61499 is the preferred solution as it shares similar design methodologies to IEC 61850 systems. IEC 61499 is an open standard for the design of control and distributed system. Like IEC 61850, IEC 61499 utilizes system level approach in designing distributed systems and the function block artifacts in IEC 61499 are able to fully model the information encapsulation of each IEC 61850 logical nodes. The validity of an IEC 61850 and IEC 61499 solution is outlined in [8] and ongoing research in [9, 10] shows the potential of a solution combining IEC 61850 and IEC 61499.

III. MOTIVATION

As mentioned in the previous chapter, there is currently no single standard which formalizes every aspect for a Smart Grid system. However, standards such as CIM, IEC 61850 and IEC 61499 could be harmonized to form a single Smart Grid standard allowing interoperability between the three standards. IEC 61850 and IEC 61499 are two standards which have been used in the Smart Grid Automation research. The Intelligent Logical Node (iLN) architecture [11], one of the backbone of the SysGrid tool creates the connection between the IEC 61850 and IEC 61499 standards as shown in [11, 12]. This work is an extension to the work in [11, 12] aiming at a systematic approach to designing substation automation systems centered around the iLN architecture based on MBSE. The proposed solution realized in SysGrid adopts systems engineering designing principles from IEC 61850 to automatically generate automation software and co-simulation based centered on the iLN architecture. The work described in this paper details the SysGrid engineering process from requirements to the generation of usable distributed

automation control code to a co-simulation environment which has not yet been addressed in the domain. In-depth discussion of the co-simulation environment and the transformation rules between IEC 61850 and IEC 61499 are not covered in detail in this paper. Detailed discussion of the co-simulation environment and the Hardware-In-Loop (HIL) can be found at [11] and [13].

IV. POWER SYSTEM AUTOMATION DESIGN PROCESS BASED ON IEC 61850

The core component which makes up SysGrid supports the design process of IEC 61850 based systems described in [14]. In this process, specifications are captured in an IEC 61850 System Specification Description (SSD) file and the results of the design process are formally captured in a System Configuration Description (SCD) file. The adopted IEC 61850 design process for SysGrid is depicted in Fig. 1.

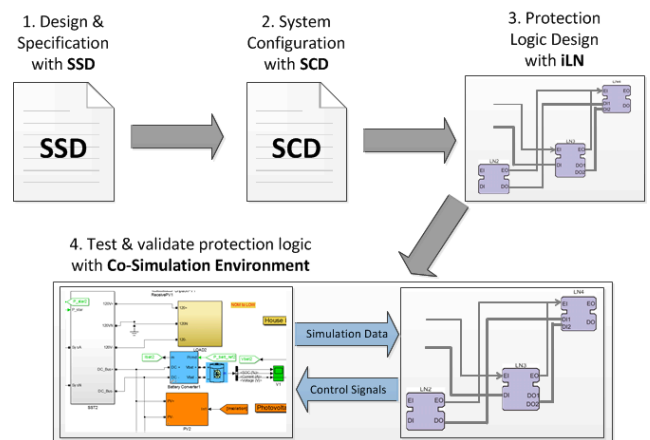


Fig. 1. Design process of SysGrid (From requirements to Co-Simulation).

The first step is to produce the Single Line Diagram (SLD) and formally capture the functional requirements in IEC 61850 SSD files. All functions at this stage should be abstracted from any implementation to allow optimization [14]. IEC 61850 offers the concept of Logical Nodes (LNs) as formal definitions of the functions [14] and equipment in a XML format.

The second step is the engineering of the substation at the system level. The result of this process is captured in the IEC 61850 SCD file, which contains configuration for IEDs and the communication configuration of the devices in the system. There are 5 sections in the SCD file. These sections are the header section, the substation section, the IED section, the communication section and lastly, the DataTypeTemplate sections [2]. The SCD file describes the configuration of all the IEDs in the system. The IED section contains access points, servers, communication control blocks and the LNs. LN types used in the design are defined in the DataTypeTemplates section, which represents a signal list.

The third step is to generate control and automation logic corresponding with the desired functions as shown in Fig. 1. SysGrid can generate an executable FB network from the SSD file, in which case functional simulation can be performed at the design stage with the help of the co-simulation environment. In addition to SSDs, SysGrid is also capable of importing SCD files, which generates a complete IEC 61499 distributed system configuration [3]. All specified IEDs, network topology and automation functions in the SCD will be generated in the corresponding IEC 61499 distributed system. SysGrid will offer suggested connections between LN FBs,

and pre-connect the generated FB network according to the specification.

The transformation of the IEC 61850 hierarchy into an IEC 61499 equivalent is governed by a rule set. Rules define the mapping of IEC 61850 artefacts to IEC 61499, e.g. a system level SSD file is represented as an IEC 61499 application; an IED is mapped directly to an IEC 61499 device; and a LN corresponds to a composite FB. The generated IEC 61499 system configuration represents an automation, control and protection solution specified in accordance with customer requirements and designed by an engineer. The solution is based on the intelligent Logical Node (iLN) architecture, which will be described later in the paper.

The last step of the process is to validate the application via co-simulation. The co-simulation environment allows for validation of the system design and can also be used to estimate communication load, performance and completeness, etc. Fig. 2 illustrates the co-simulation concept. On one side, a specific power system simulation package (e.g. Matlab SimPowerSystems, PS CAD, etc.) models the target utility (e.g. substation and distribution or transmission network). On the other side, SysGrid models the desired automation, control and protection logic. During the simulation process, simulated data is exchanged between the utility simulation plant and the control model to validate the control system.

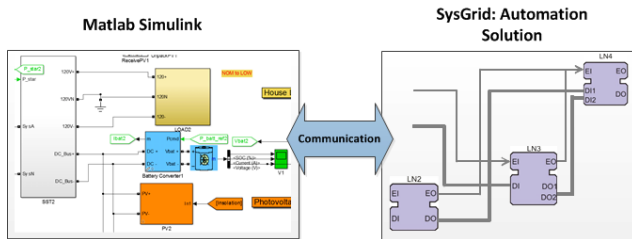


Fig. 2. Co-Simulation Environment.

V. SYSGRID: ARCHITECTURE AND CAPABILITIES

SysGrid consists of three main modules as shown in Fig. 3. The three modules are the system configurator module, the generation module and the co-simulation module. SysGrid presents both system and IED configurators in a single tool adopting the IEC 61850 system engineering process. The first module represents the IEC 61850 system configurator. The system configurator module includes the schema editor for editing or designing SLD, SSD and SCD configuration files. In the SSD/SCD editor, customer requirements are captured as IEC 61850 LNs. Moreover, SysGrid provides the ability to easily sketch automation, control and protection schemes on top of the SLD as if using paper. This functionality is implemented in the schema editor.

In the Generation module, SysGrid can parse the system design to identify physical components, functions and functional interactions. Using a library of IEC 61499 iLNs FB, the tool generates an executable IEC 61499 application directly from the SCL specification. SysGrid generates the corresponding system configuration with the defined network topology and device set. Signal engineering while allocating functions to devices (function distribution) is supported by automated configuration of the detailed data flows between IEDs and allocation of communication addresses (GOOSE datasets, signal inputs to clients, sub-networks). A custom library of iLN FBs is created according to the DataTemplate section of the SCL file. SysGrid will also

generates a Matlab simulation model of the system from the SLD contained in the SSD and SCD files for the co-simulation module. SysGrid is also capable of importing ICD and CID files for individual device configuration and exporting of CID files containing the necessary information from the imported SCD file.

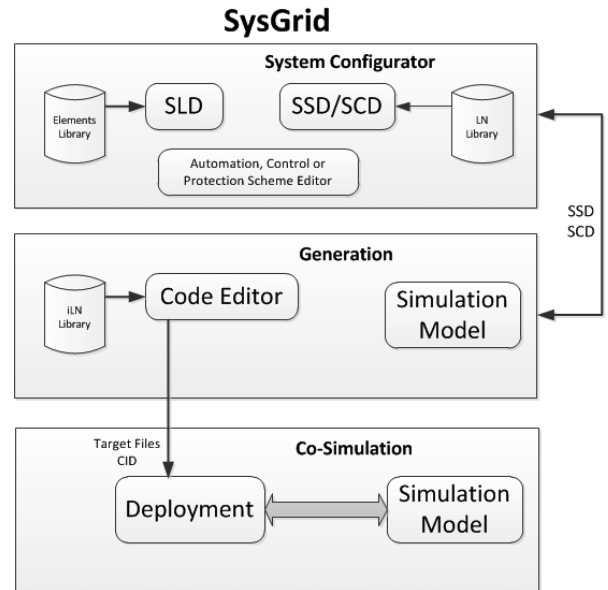


Fig. 3. SysGrid Architecture.

In the co-simulation module, SysGrid performs functional simulation of the designed control logic in conjunction with the utility model. The automation, control and protection code can be downloaded to the simulated devices or deployed to real hardware. The tool provides a real-time, event-driven simulation via a GUI, e.g. introducing a phase-to-ground fault into the model of distribution network. Additionally SysGrid supports hardware-in-the-loop testing with a controller, protection device or other equipment.

SysGrid as a smart grid substation automation tool which supports the system design process from the designing of SLD diagrams to the deployment of the validated automation solution to physical devices. Throughout the design process, SysGrid maintains compatibility with other standards-based tools, by supporting standardised file formats according to IEC 61850 SCL languages i.e. SSD, SCD, ICD, CID and IID.

VI. CASE STUDY: DISTRIBUTED PROTECTION APPLICATION DESIGN

This case study illustrates the capability of the proposed design process in a distributed protection application example. The example, adopted from [12] illustrates distributed protection with GOOSE messages. Three types of protection schemes are implemented: distribution bus, selective backup and sympathetic tripping protection schemes.

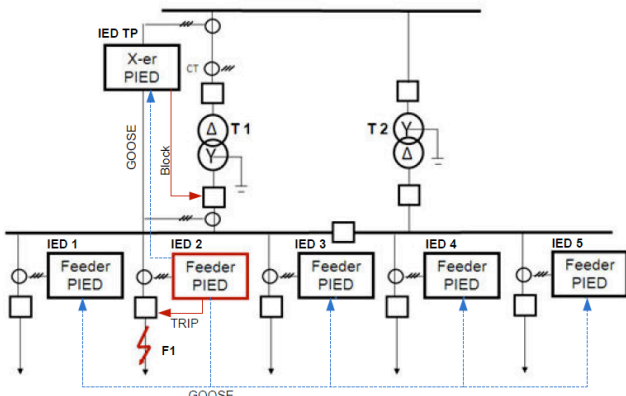


Fig. 4. Sample distribution network: distributed protection application.

The scenario is applied to the distribution network shown in Fig. 4. The network consists of a distribution bus, two transformers and five feeders. The transformer protection IED (IED TP) is located at transformer T1, protecting the associated circuit breakers. Each feeder has a feeder protection IED (IED1 - IED5) and a circuit breaker to clear faults.

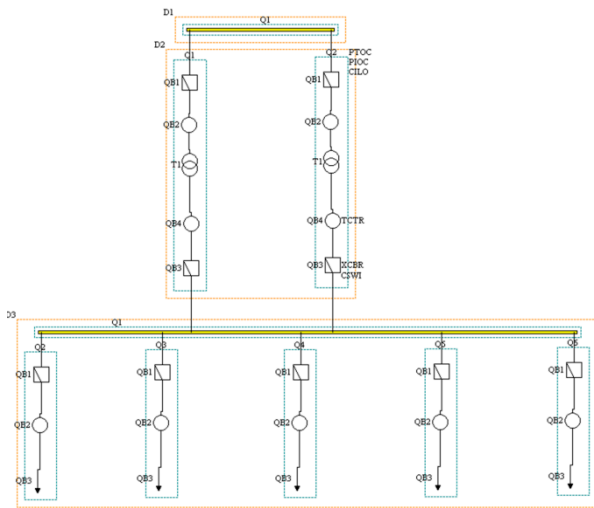


Fig. 5. SLD of the desired system with functions allocated to Logical Nodes.

The first step is to design the substation SLD in the SLD editor and specify the requirements for the desired protection schemes. Fig. 5 shows the SLD of the case study circuit and the functional specifications are represented as IEC 61850 LNs. Instrument transformers for current measurements are modeled with TCTR LNs placed on the power transformer and each feeder. Overcurrent protection is modeled with PIOC LNs in the protected bays. Protection trip conditioning, needed for multiplexing signals from three protection schemes, is modeled with PTRC LNs. Interlocking functions are modeled with a CILO LN placed in the transformer bay. Circuit breakers are modeled with XCBR LNs controlled by CSWI switch control LNs.

The system configuration is shown on Fig. 6 in the form of a SCD file. The SCD file defines the selected IEDs and allocates functions (LNs) to devices (IEDs). As shown in Fig. 6, the system is called S1 and has 5 feeder IEDs and one transformer IED. Having defined the system configuration, the ensuing step is to generate IEC 61499 system configuration and code the automation, control or the protection logic.

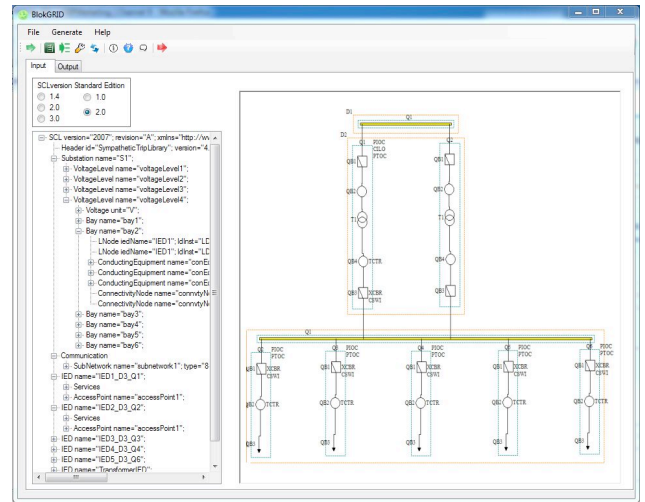


Fig. 6. SLD with allocated IEDs. System configuration.

Fig. 7 demonstrates the process of automatically generating FB networks from the system configuration. For each LN instantiated in SSD/SCD file, an equivalent iLN FB is automatically generated.

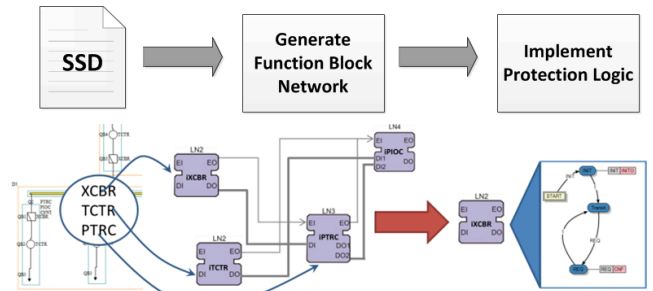


Fig. 7. SysGrid: Generation principle.

Fig. 8 illustrates the full IEC 61499 system configuration generated by SysGrid in accordance to the mapping rules previously described in section IV. The FB system comprises of an application called S1 and six devices as shown in Fig. 8a. Each feeder has 8 LNs including LN0 and LPHD. The transformer has 13 LNs as illustrated in Fig. 8b. Fig. 8b shows the application view of the designed system automatically generated from an SSD file in which LNs are not yet allocated to IEDs. In an SCD file the LNs would be allocated to IEDs – these associations would be imported and kept. In the generated IEC 61499 system configuration, iLNs at the device level are mapped to corresponding iLNs at the application level. A custom library is generated according to DataTypeTemplate section of the SCL file as illustrated in Fig. 8b. The iLNs used in the FB networks are instantiated from this library.

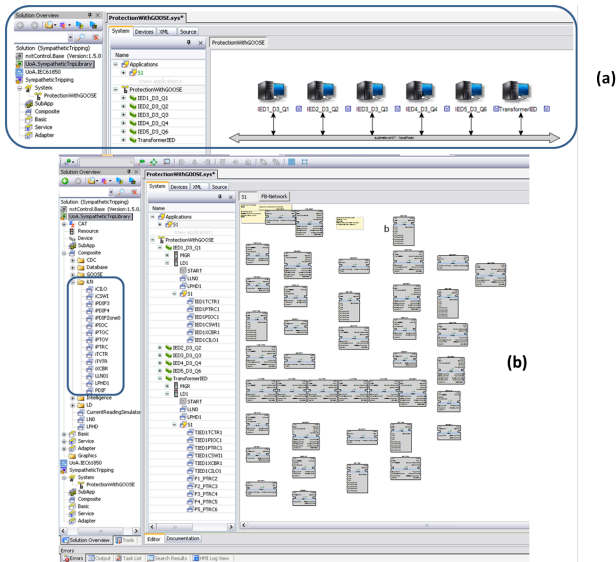


Fig. 8. SysGrid: Generated IEC 61499 system configuration.

SysGrid also contains a logic editor allowing automation, control and protection logic to be implemented at the system level without allocating functions to devices. The logic is implemented using the iLN architecture proposed in [11].

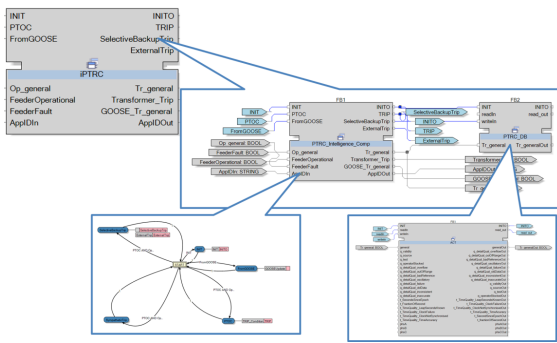


Fig. 9. LN: iPTRC logical node architecture.

An iLN is a composite FB capable of simulating or even completely implementing an IEC 61850 LN. It comprises a database FB and an intelligence FB as shown in Fig. 9. The database FB contains the data of the corresponding IEC 61850 LN information model. The intelligence FB implements the automation logic of the LN. With SysGrid systems, designers can use proprietary iLNs libraries provided by IED vendors or create custom iLNs having novel and/or advanced functionality as required for Smart Grid applications. An example of the intelligence of the iLN iPTRC for the case study application is shown in Fig. 9. This FB implements a simplified algorithm for protection trip conditioning. The iPTRC iLN merges the transformer protection trip signal and the trip signals from overcurrent protection IEDs.

Once the iLN are generated, logical event and data connections can be made between iLNs to create a FB network having the desired automation, control and protection functionality. In the case study example, iLNs are connected to perform distributed protection schemes. Fig. 10 presents the complete protection application ready for functional simulation.

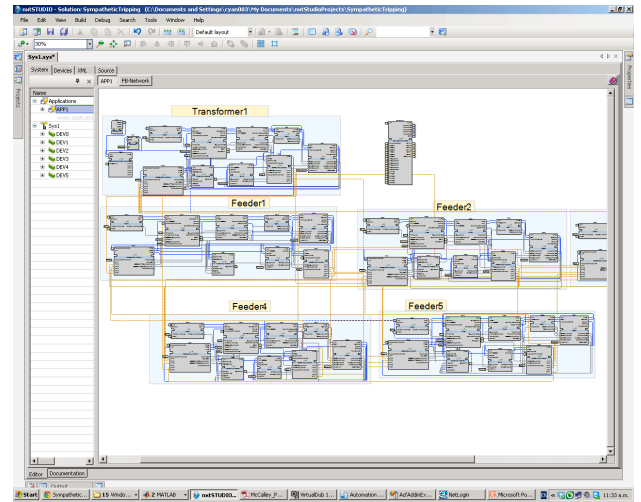


Fig. 10. Complete IEC 61499 distributed protection solution.

The last step of the design process is testing and validation in the co-simulation environment supported by SysGrid. The co-simulation environment is similar to that used in [11] as shown in Fig. 2. The Matlab Simulink model periodically sends simulated data to the IEC 61499 program. The IEC 61499 processes the incoming simulated data and sends control signal back to the Matlab Simulink model if necessary. In addition, simulated faults such as phase-to-ground fault could be inserted into the Matlab model to verify or validate the FB control system. Fig. 11 shows the result of one such validation test. A fault is inserted into feeder 2 in the running Matlab simulation. The IED on feeder 2 and the transformer IED both detect the fault. However, the IED on feeder 2 informs transformer IED and the adjacent feeder IEDs about the fault via GOOSE message. When the neighbouring IEDs receive the GOOSE message, each will adjust its overcurrent threshold accordingly for the duration of the inrush period to protect against sympathetic tripping of healthy feeders.

A distributed protection solution using GOOSE messages has been designed, developed and validated via simulation within the SysGrid environment. Computer aided design has facilitated system specification, signal flow engineering and system configuration. The logic editor has facilitated the development and/or composition of system functionality. Finally the co-simulation environment has helped to validate the design by demonstrating correct behaviour. The developed code can be deployed to real hardware and readied for commissioning tests.

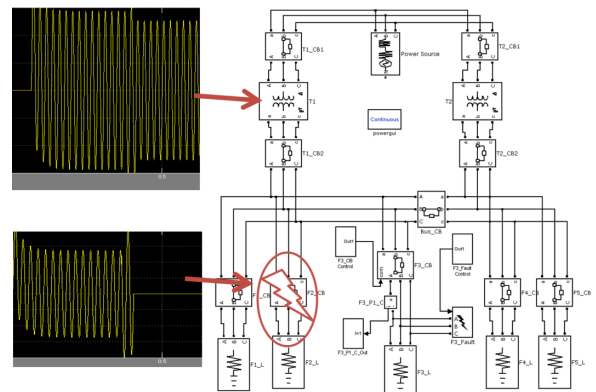


Fig. 11. SysGrid: Co-simulation results.

VII. CONCLUSION AND FUTURE WORK

With SysGrid the system engineering process can be easier, faster, resilient to human errors, and more affordable than the current IEC 61850 system engineering process. In the current process a series of dedicated tools must be used, leading to a disconnected process in which incompatibilities between proprietary tools and their limited capabilities are detrimental to both speed and effectiveness. SysGrid opens the full potential of the IEC 61850 standard, which was developed with a view to minimizing such problems.

Benefits of the proposed engineering process include reduced engineering costs, better validated Smart Grid applications and ability to see the impact of intelligent automation on electricity network performance. SysGrid addresses the design challenges of complex Smart Grid automation systems with distributed control. It aims to support Smart Grid automation system engineering, starting with requirements and arriving at executable code – a distributed software solution that is validated and ready for commissioning.

At this stage the tool is a prototype. Future work involves improving practicality and addressing design challenges, with the ultimate goal of producing a fully functional commercial product for use in Smart Grid automation solution engineering.

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