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Antoine Labonne, Raphaël Caire, Thierry Braconnier, Laurent Guise, Mario Jardim, et al.. Teaching digital control of substation and IEC 61850 with a test bench validation. *IEEE Transactions on Power Systems*, 2020, 36 (2), pp.1175-1182. 10.1109/TPWRS.2020.3010446 . hal-02907397

HAL Id: hal-02907397

<https://hal.science/hal-02907397>

Submitted on 3 Feb 2022

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Teaching digital control of substation and IEC 61850 with a test bench validation

Antoine Labonne, Raphael Caire, *Senior Member IEEE*, Thierry Braconnier, Laurent Guise, Mario Jardim, Nouredine Hadjsaid, *Senior Member IEEE*

Abstract--This paper proposes an original Smart-Grid test bed aimed at teaching the IEC 61850 standard to students and professionals. It includes emulation of medium voltage loads and generators, with a supervisory control and data acquisition system. With this test bed, lab classes focused on the setup and configuration of protection relays using semantics of xml language are proposed. For this, GOOSE services and their functionalities are taught and tested with experiments involving real cases. The presented lab classes are part of a dedicated complete pedagogic module comprising lectures and experiments. Through the development, the test and the deployment of their own solutions in an actual distribution grid, the students learn by integrating theory and practice through the complete chain of Smart-Grid solutions: from the electrical to the communication layers.

Index Terms—Power engineering education, Distribution grid, Experimental platform, Intelligent Substation, Protection relay, Smart-Grids, Standard, IEC 61850.

NOMENCLATURE

ANR: French equivalent of US National Science Foundation
ANSI: American National Standards Institute
ANSI A51: Standard dedicated to overcurrent protection
BR-IEDn: Breaker of IEDn
CET850: Schneider Electric Software
CID: Configured IED Description
DNP: Distributed Network Protocol
ENSE3: Ecole Nationale Supérieure de l'Energie, l'Eau et l'Environnement
G2Elab: Grenoble Electrical Engineering Laboratory
GOOSE: Generic Oriented Object Substation Event
ICT: Information and communication technology
IEC 61850: Standard for Smart Grids
IED: Intelligent Electronic Device
IED Scout: Software of Omicron Company
LD: Logical Device
LN: Logical Node
OSI: Open System Interconnection
PTOC: Protection Time Overcurrent
PTRC: Protection Trip Conditioning
PREDIS: Production et Réseaux Energies DIStribuées
Ring LAN: Ring Local Area Network
SAS: Substation Automation System
SCADA: Supervisory Control And Data Acquisition System
SCD: Substation Configuration Description

SCL: Substation Configuration Language
Sepam: Schneider Trademark (protective relays)
S84: Sepam type 84
SINARI: Sécurisation des Infrastructures et Analyse des Risques (French research project funded by ANR)
SV: Sample Value
Wireshark: Open source Software

I. INTRODUCTION

SINCE the early 2000s, the world of electrical network operations has been evolving steeply. The trend is towards the decentralization of automation and to promote the interoperability of systems and electrical networks in real time. To enable this, several standards are emerging and constantly evolving [1][2]. Among them, the IEC 61850 standard [3] introduces convergence to common data models, which is the focus of this paper. In order to bring these computer models closer to real processes, a complete teaching method addressing this subject within a substation with real protection relays is proposed. Several articles address different topics of the IEC 61850 standard. Among these, K. Kaneda *et al.* [4] focus on Substation Automation System and design a method around Ring LAN. Many details are found on the Logical Node family. S. Roostae *et al.*, [5] address peer-to-peer (horizontal) communication, GOOSE messages, and the main features of IEC 61850. Q. Song *et al.* [6] concentrate on two items: the analysis and comparison of pilot application and control functions. D. M. E. Ingram [7] focuses on bus protection performance with a real time digital simulator and real substation devices. They use Sample Value (SV) measurements and GOOSE at the Merging Unit to test the transformer protection relay. Finally, S. Kariyawasam *et al.* [8], C. Ghafari [9], A. Apostolov [10] are closer to the applications that are devoted in this article. They propose different exercises around IEC 61850 based on Substation Automation System (SAS). Their originality is in the use of real time target in the protection scheme. In the same way as the previously cited authors, practical labs based on the semantics of the IEC 61850 standard are proposed here. Compared to [7], an additional view on GOOSE messages with real components (protective relays) in the different levels (process, bay and substation) is addressed. Sample Values as [7][11] are not covered, but instead, tools such as Wireshark and IED Scout [12] are introduced in complement to courses and labs.

This work was supported in part by the Agence Nationale de la Recherche (ANR) under the grant ANR-09-SECU-11 and Schneider Electric.

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This article aims to summarize part of a set of courses presented at a Master’s Degree in Grenoble INP-Ense³. All courses cover a duration of 60 hours and introduce ICT tools for Smart Grid engineers. The topics can be split into four axes:

- The Big data (10 hours of lectures and 4 hours of computer lab with Mango DB software).
- Cybersecurity (12 hours of lectures).
- The SCADA (10 hours of lectures and 4 hours of computer lab with Lynx industrial SCADA software).
- The IEC 61850 Standard (4 hours of lectures + 4 hours of computer tools + 12h of labs).

In this paper, only the last part of the last topic (labs on the IEC 61850 Standard) is discussed. The lab (12h) is broken down as follows: 4 hours of exchanges on IEC 61850 and 8 hours of practice using the platform presented below. The PREDIS platform [13] and technological tools are also presented to students.

II. IEC 61850 INTRODUCTION AND SEMANTIC

To introduce the course and labs, the Smart Grid Architecture Modeling (SGAM) is presented. Labs concern the fields indicated by the black discs in Fig. 1. The topics addressed here are Power System Equipment and Energy conversion, and feeder automation for the domain of Distribution and Transmission networks. In order to illustrate the IEC 61850 standard, Fig. 2 shows the different levels of communication from equipment to Substation. Students start to discover several protocols (oval shape in Fig. 2), generally used before IEC-61850 description, such as Modbus, DNP, Profibus, Fieldbus, and so on. In order to map the structure and connect the devices shown in Fig. 2, students use as basis the different layers of the Open System Interconnection (OSI) model proposed by the International Organization of Normalization [15]. IEC 61850 focuses on the second layer (Data Link) of the OSI description. Essentially, the labs address sections 5, 6, 7, 8 and 9 of the IEC 61850 standard (highlighted in Fig. 3).

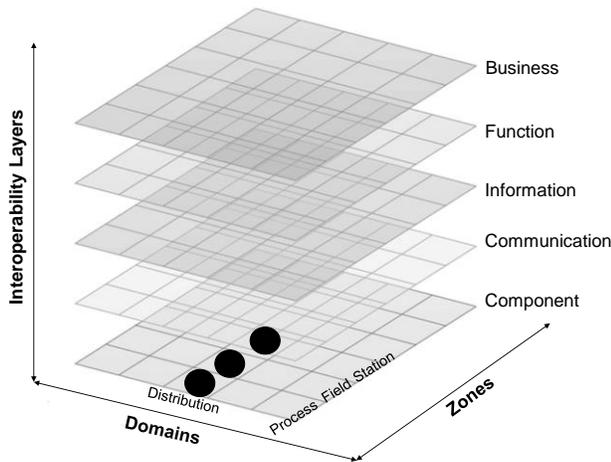


Fig. 1. Smart Grid Architecture Model. Domains and zones addressed in the course are indicated by the black discs [14]

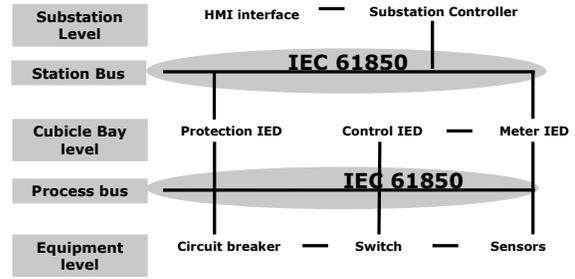


Fig. 2. Smart Substation Communication Structure using IEC-61850

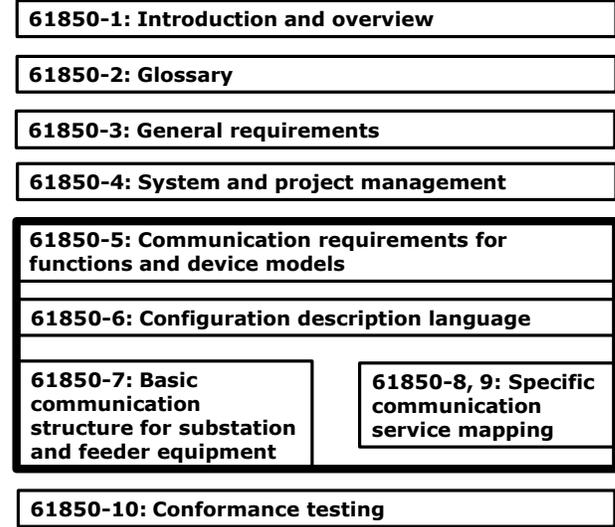


Fig. 3. Description of IEC 61850 chapters

III. THE EXPERIMENTAL PLATFORM USED IN THE LAB CLASS

All labs are tested with realistic applications on a Smart Grid Intelligent Substation (see Fig. 4). This test bed was initially developed as part of the French national funded ANR ‘SINARI’ Project to study the vulnerabilities that emerge between power systems and communication networks [16]. As mentioned in [16], this platform has four physical control and automation devices, a station bus and circuit breakers configured to reproduce their “in-field” performance.

TABLE I
Logical Nodes (LN) classes described in IEC 61850-7

Logical Node	Group (Family)
A	Automatic control
C	Supervisory control
D	Distributed energy resources
F	Functional blocks
G	Generic function references
H	Hydro power
I	Interfacing and archiving
K	Mechanical and non-electrical primary equipment
L	System logical Nodes
M	Metering and measurement
P	Protection functions
Q	Power quality events detection related
R	Protection related functions
S	Supervision and monitoring
T	Instrument transformer and sensors
W	Wind power
X	Switchgear
Y	Power transformer and related functions
Z	Further (power system) equipment



Fig. 4. Smart Grid Intelligent Substation coupled to a linear power amplifier

It could also be plugged to a real reduced scale distribution network [13]. For all the labs presented below, current generators are mainly used to test real cases. The next chapters address different experiments using advanced services, such as Generic Oriented Object Substation Event (GOOSE). The Network configuration of a Smart Grid Intelligent Substation platform is described in Fig. 5.

IV. LABS DESCRIPTION

The course comprises five different experimental labs. The goal is to explain to the students the content of the IEC standard and the semantics of each message service for the network. It emphasizes the setting up procedures and the utilization of Generic Oriented Object Substation Event (GOOSE). Labs 0 to 4 propose several tests, including the configuration of the network and the notions addressed during the lectures. The chapter “Educational Outcomes” discusses the main results and outcomes.

A. System modelling and configuration (lab 0 and lab 1)

Many stakeholders are currently considering IEC 61850 only as a communication protocol which brings benefits for real-time operation on the field. Actually, IEC 61850 can bring much more than this and appears as a key mean along the whole life cycle of any distribution utility smart asset. It is important to let students understand that IEC 61850 can be used very efficiently with the objective to capture user requirements, thanks to a formal approach relying on IEC 61850 principles and language. This lab puts into practice the main elements that are the basis for such a top-down system approach, more specifically:

- The different namespaces (related to substation, feeder, distributed energy resources), already published or coming-up
- The three main language domains which are covered by IEC 61850: the process side (encompassing the electrical topology and associated equipment, as well as the associated functions), the functions side, and finally the communication side.

The first experimental class – lab 0 – intends to introduce a large set of examples. Different solution sections, primary and secondary devices as well as distributed functions allow the students to define the solution components, their frontiers and their functional dependencies.

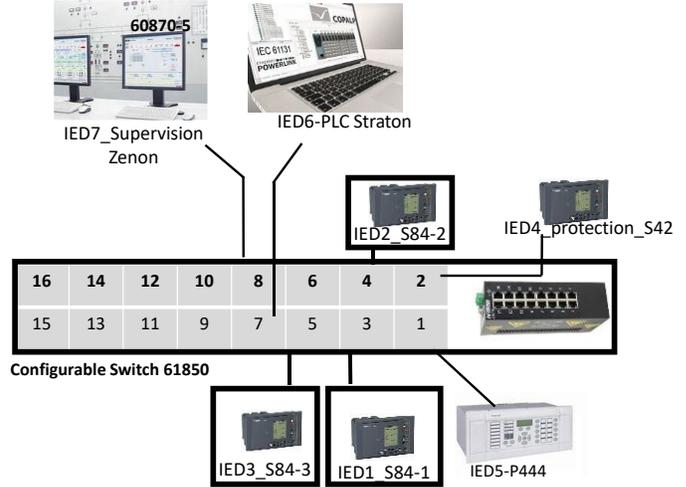


Fig. 5. Network configuration of a Smart Grid Intelligent substation

The objective of lab 1 is to configure and set up the Intelligent Electronic Devices (IED) of a Smart Grid Intelligent Substation platform. Students create CID (Configured IED Description) and SCD (Substation Configuration Description) files for the Network configuration. Fig. 6 shows a simplified configuration for all the labs corresponding to the highlighted IED. In this session, students discover the semantics of the IEC 61850 standard, re-using the knowledge acquired during the previous lab. They use Schneider Electric software (CET 850) and generate their configuration description files (CID and SCD). Then they edit these files with a text editor to understand their semantics. The SCD file shown in Fig. 7 describes the configuration of the equipment in Fig. 6.

Afterwards, students distinguish the differences between the “Substation Configuration description” and the “Configured IED description”. They can then edit their own files to improve the description of the substation. In this lab, the addressing plan of devices communication is also provided. They are then able to move forward and explore all the remaining labs described in the following sections.

B. GOOSE Services generation and settings (lab 2 and lab 3)

The main objective is to use and set "GOOSE publisher/subscriber services" from IEC 61850 with Smart Grid Intelligent Substation between different Intelligent Electronic Devices (IED).

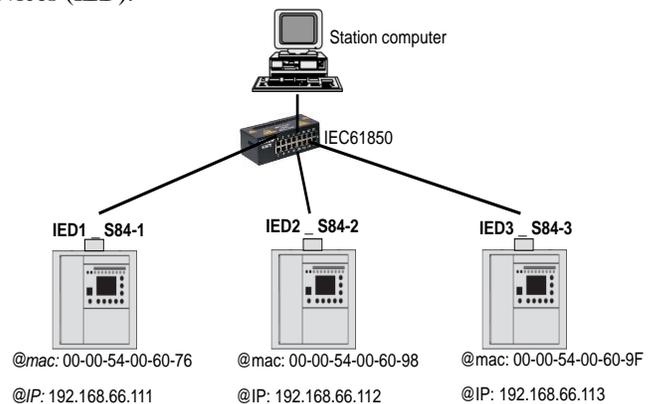


Fig. 6. Simplified IP configuration for an intelligent substation

In this work, the focus is on IED1 (S84_1), IED2 (S84_2) and IED3 (S84_3). For all the labs on the GOOSE services generation, the organization of a GOOSE model is reminded. Students are guided through the creation of a dataset and GOOSE control block. For this, they have to closely consult the IEC 61850 Standard [3].

To illustrate the principle of the GOOSE services implementation, lab 2 (load shedding) is proposed as illustrated in Fig. 8. This is a lab designed to foster the understanding of GOOSE operation settings. It uses XCBR (switchgear and circuit breaker descriptions) as described in Table I.

The goal is to use GOOSE publisher/subscriber services to operate the devices and test this communication through the platform.

By way of example, if circuit breaker BR-IED1 must cause the opening of the other two circuit breakers (BR-IED1 and BR-IED3), the procedure begins with the creation of a dataset (DS1) in an appropriate logical node of the physical device (BR-IED1). The data attribute to be changed is "stVal", inside data class "Pos". Data "Pos.stVal" stands for the current state of the circuit breaker - open or closed. To be sent to other devices, a GOOSE control block (CB1) must be created, as described below. Inside the GOOSE control block, the dataset is selected and many settings may be modified (such as re-sending time for the communication). Then, students need to set up the publisher (IED 1) and the assignment of the messages for subscribers (IED2 and IED3). Students create CID and SCD files before checking the behavior on the Smart Grid Intelligent Substation platform. Thanks to this, the learners understand firstly the logic behind GOOSE services. Then, they check their functionalities for each lab. Thereafter, the use of PTRC and PTOC GOOSE services (lab 3) are presented. The aim of lab 3 (load shedding by current protection) is to compare two methods of protection (Logical Node P as presented in Table I).

```

<SubNetwork name="IEC61850">
  <ConnectedAP apName="AP1" iedName="IED1">
    <Address>
      <P type="IP" xsi:type="tP_IP">192.68.66.111</P>
      <P type="IP-SUBNET" xsi:type="tP_IP-SUBNET">255.255.255.0</P>
      <P type="IP-GATEWAY" xsi:type="tP_IP-GATEWAY">0.0.0.0</P>
      <P type="OSI-PSEL" xsi:type="tP_OSI-PSEL">00000001</P>
      <P type="OSI-SSEL" xsi:type="tP_OSI-SSEL">0001</P>
      <P type="OSI-TSEL" xsi:type="tP_OSI-TSEL">0001</P>
    </Address>
  </ConnectedAP>
  <ConnectedAP apName="AP1" iedName="IED2">
    <Address>
      <P type="IP" xsi:type="tP_IP">192.68.66.112</P>
      <P type="IP-SUBNET" xsi:type="tP_IP-SUBNET">255.255.255.0</P>
      <P type="IP-GATEWAY" xsi:type="tP_IP-GATEWAY">0.0.0.0</P>
      <P type="OSI-PSEL" xsi:type="tP_OSI-PSEL">00000001</P>
      <P type="OSI-SSEL" xsi:type="tP_OSI-SSEL">0001</P>
      <P type="OSI-TSEL" xsi:type="tP_OSI-TSEL">0001</P>
    </Address>
  </ConnectedAP>
  <ConnectedAP apName="AP1" iedName="IED3">
    <Address>
      <P type="IP" xsi:type="tP_IP">192.68.66.113</P>
      <P type="IP-SUBNET" xsi:type="tP_IP-SUBNET">255.255.255.0</P>
      <P type="IP-GATEWAY" xsi:type="tP_IP-GATEWAY">0.0.0.0</P>
      <P type="OSI-PSEL" xsi:type="tP_OSI-PSEL">00000001</P>
      <P type="OSI-SSEL" xsi:type="tP_OSI-SSEL">0001</P>
      <P type="OSI-TSEL" xsi:type="tP_OSI-TSEL">0001</P>
    </Address>
  </ConnectedAP>
</SubNetwork>

```

Fig. 7. SCD file semantics

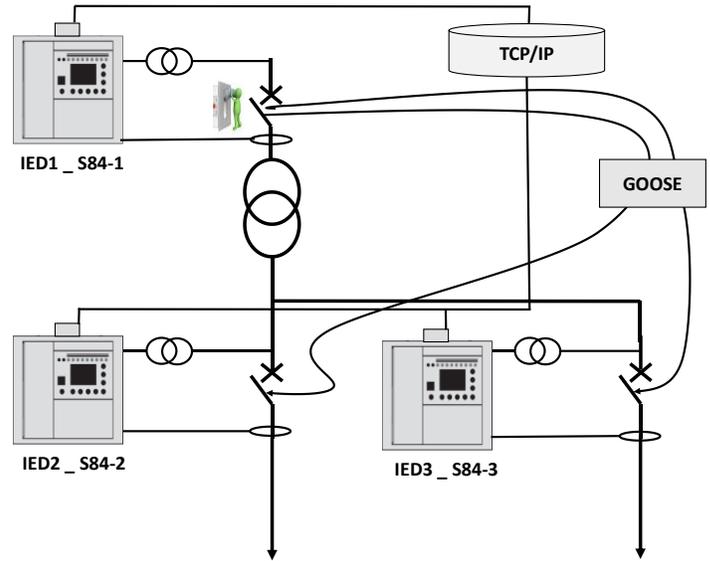


Fig. 8. Schematic description of Lab 2

TABLE II
Main settings for Smart Grid Intelligent Substation IED platform

Device	Name	IP address	MAC address
Protective relay MV	IED1,S84_1	192.168.66.111	00.00.54.00.60.76
Protective relay MV	IED2,S84_2	192.168.66.112	00.00.54.00.60.98
Protective relay MV	IED3,S84_3	192.168.66.113	00.00.54.00.60.9F

In several applications, "overload and phase-to-phase short circuit", like Protection Time over Current (PTOC, ANSI A51) and classical protections, such as Protection Trip conditioning (PTRC) are often used. Lab 2 allows us to test separately these two types of protection by using GOOSE services. Fig. 9 shows the description of Lab 3.

Following the procedures described in Lab 2, students create two others GOOSE services. The GOOSE messages allow the opening of all the breakers (BR-IED2, BR-IED3) below the secondary of the transformer when IED1 detects an overcurrent.

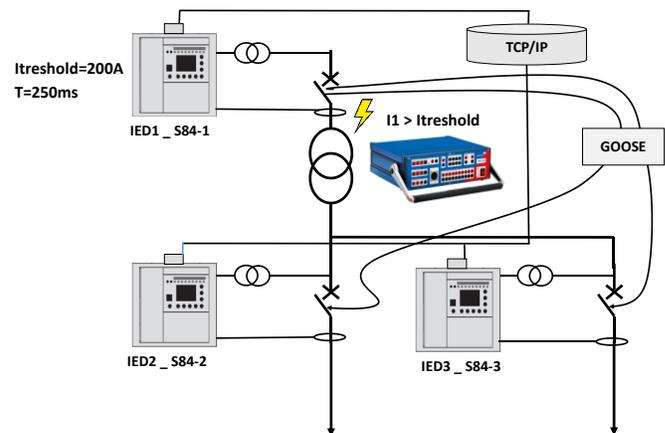


Fig. 9. Schematic description of Lab 3

The flowchart depicted in Fig. 10 describes the steps of this lab. They set a threshold current at 200 A during a period of 250 ms as described in Fig. 9. Then, students set a different transforming ratio for the current transformer (250 A / 5 A). When the breaker of IED1 (BR-IED1) is open due to a short circuit at the primary of the transformer, the GOOSE services must allow the opening of all the breakers (BR-IED2, BR-IED3) at the secondary of the transformer.

TABLE III
Publisher settings and subscribers assignments

IED1 (publisher) settings					
Communication					
Substation					
S84_1					
LD LD0					
GC CB1					
DS DS1					
[ST] LD0.XCBBR1.Pos.stVal					
IED2 and IED3 (subscribers) assignation					
IED Name	DA	Description	G401	G402	G403
S84_1	QR	Quality			
S84_1	QD	Quality Dataset			
S84_1	[ST] LD0.XCBBR1.Pos.stVal				X

The learners use current generators for generating and analyzing voltage and current waveforms (I1 and Ithreshold in Fig. 9). Before testing their configurations, they must set the transformation ratio of the current transformer to check the real current and voltage.

They compare the duration of the onset of the two GOOSE protections (PTOC and PTRC). Students must describe the periodicity of GOOSE messages and must detect the events. Then, they create CID and SCD files before comparing PTOC and PTRC.

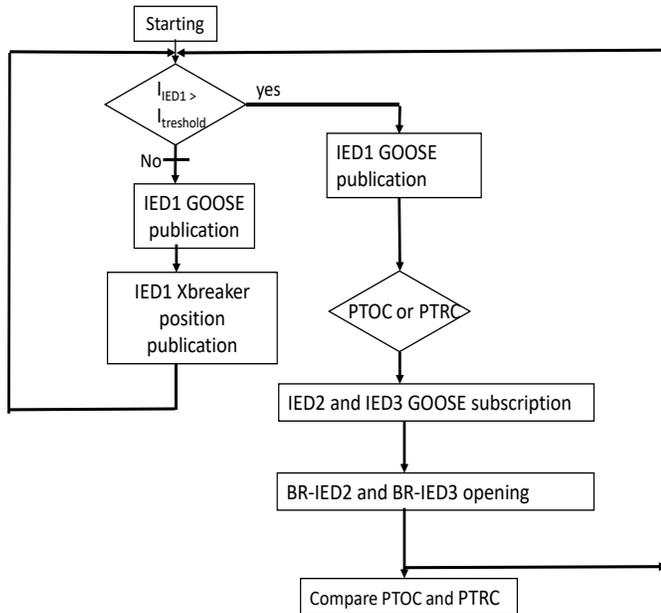


Fig. 10. Flowchart of Lab 3

C. Representative results and analysis

Representative results of lab 2 are presented on Fig. 11 and Table IV. Table IV aggregates the results of both strategies: PTOC and PTRC. Students use IED Scout and Wireshark in order to compare time delay and triggering analysis as shown on Fig. 11. Students summarize their results using representations such as the one shown in Fig. 12. They compare the two strategies and conclude that PTOC is faster than PTRC and that PTRC is not constrained to the delay of 250 ms.

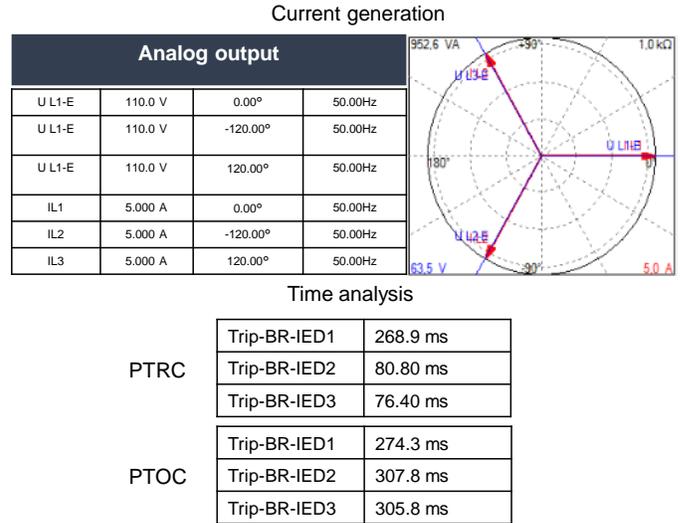


Fig. 11. IED Scout Analysis Time

TABLE IV
PTOC and PTRC description for External Trip Lab 2

GOOSE	Publisher	Subscriber	Overcurrent triggering	Programming description
PTOC	IED1	IED2 IED3	IED1 24.3 ms IED2 57.5 ms IED3 55.8 ms	LD0/A51.PTOC1.op.general
		IED2 IED3	IED1 18.9 ms IED2 61.9 ms IED3 57.5 ms	LD0/PTRC1.blkind1.stVal

For their assessments, students use two counter systems (Omicron CMC356) and numerical tools such as Wireshark or IEDscout (described in lab 3). At the end of lab 2, in order to emphasize the non-deterministic time for these two-overcurrent protections, Table V is provided to students.

TABLE V
PTOC and PTRC comparison for lab 2

IED	Trip Time PTOC (ms)	Standard deviation (ms)	Variance	Trip Time PTRC (ms)	Standard deviation (ms)	Variance
1	270.4	5.5	30.3	272.2	2.7	7.2
2	304.5	6.3	39.2	77.6	3.2	10.3
3	300.9	5.8	33.2	80.4	3.0	8.8

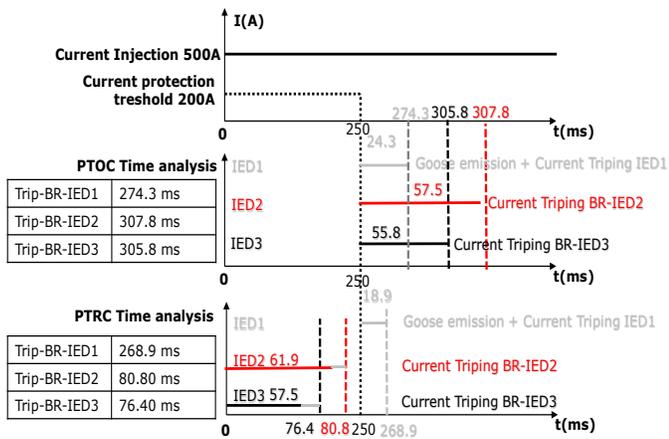


Fig. 12. Time analysis for PTOC and PTRC

D. Sniffer and IED Scout utilities (lab 4)

Lab 4 deals with data analysis with Wireshark and IED Scout software. In this lab, keeping the premise of lab 3, additional information on frequency, quality, power, current, among others, are added. This was done to explore the basic functionalities of two snippet software tools, IED Scout and Wireshark. IED Scout provides access to the IEDs and performs numerous useful functions when working with them. It allows the engineer to look inside the IED and at its communication. All data model and exchanged becomes visible and accessible. This is exceptionally useful for IEC 61850 devices. On the other hand, Wireshark is a network protocol analyzer that is used for advanced functions including network troubleshooting, triggers and alerts. With these sniffers, students find their GOOSE control block, their dataset and the state position of breakers. In summary, this lab gives an overview of these tools and allows students to export data for post treatment. Fig. 13 and Table VI represent two captures of these tools with IED1.

```

Frame 11: 104 bytes on wire, 104 bytes on interface (832 bits)
  Interface id : 0 (Device\NPF_{5B6331E8-949D-4D7B-B78E-09F55B900E8F})
    Encapsulation type : Ethernet (1)
    Arrival Time : Nov 6, 2019 04 :49 :49.481026000 Paris, Madrid
    [Time shift for this packet : 0.000000000 seconds]
    Epoch Time : 1320551389.481026000 seconds]
    [Time delta from previous captured frame : 0.215342000 seconds]
    [Time delta from previous displayed frame : 0.215342000 seconds]
    [Time since reference or first frame : 2.767552000 seconds]
    Frame Number : 11
    Frame Length : 104 bytes (832 bits)
    Capture Length : 104 bytes (832 bits)
    [Frame is marked : False]
    [Frame is ignored : False]
    [Protocols in frame : eth : ethertype :GOOSE]
    [Coloring Rule Name : Broadcast]
    [Coloring Rule String : eth[0] & 1]
Ethernet II, Src : Schneide_00 :60 :76 (00 :00 :54 :00 :60 :76), Dst :
lec-Tc57_01 :00 :00
  Destination : lec-Tc57_01 :00 :00 (01 :0c :cd :01 :00 :00)
  Source : Schneide_00 :60 :76 (00 :00 :54 :00 :60 :76)
  Type : IEC 61850/GOOSE (0x88b8)
GOOSE
  APPID : 0x0000 (0)
  Length : 90
    Reserved 1 : 0x0000 (0)
    Reserved 2 : 0x0000 (0)
  goosePdu
    gocbRef : IED1LD0/LLN0$GO$GCB1
    timeAllowedtoLive : 6194

```

```

datSet : IED1LD0/LLN0$XCBR1
t : Jan 22, 23 :27 :35.814453125 UTC
stNum : 16
SqNum : 23
test : False
confRev : 1
ndsCom :False
numDatSetEntries : 1
allData : 1 item

```

Fig. 13. Data extract from Wireshark

TABLE VI
IED Scout protocol for GOOSE services detection

S84_1LD0/LLN0\$GO\$gclab2	
Details	
GOOSE control block ref.	S84_1LD0/LLN0\$GO\$gclab2
Destination MAC address	01 :0C :CD :01 :00 :00
Source MAC address	00 :00 :54 :00 :60 :76
Application ID	00
GOOSE ID	
Dataset name	S84_1LD0/LLN0\$dslab2
VLAN ID	
VLAN priority	
Needs commissioning	false
Configuration revision	2
Simulation/Test	false
Timestamp	01 :19 :40.514
Status number	32
Sequence number	0
Time allowed to live	200
Number of Dataset entries	2

E. Conclusions of experimental labs

Firstly, students start understanding the value of a top-down system modelling and then work on the network configuration of an Intelligent Smart Grid Substation. They generate CID and SCD files and use these for all the labs by downloading their configuration data into the platform. Secondly, they address advanced messages publisher/subscriber services (GOOSE) and ensure their deployment in practical labs (lab 1).

Then labs 2 and 3 allow students to use different tools with real application cases, like overcurrent protection. For this purpose, students use hardware and software configuration tools. Lab 4 explains basic functionality of two snippet software tools. These tools analyze the communication and describe the decoding message of a GOOSE. Students change the settings of the communication and then observe the datasets and the data exchange within the messages.

V. EDUCATIONAL OUTCOMES

Thanks to the learning by doing strategy, these lab classes enable students to achieve four main intended learning outcomes which would not be fully possible with other classical pedagogical approaches such as lectures or programming only. At the end of the lab classes, students are capable to:

- Use and understand IEC 61850 modelling capabilities for supporting a top-down engineering process
- Use and understand the IEC-61850 semantics of for Intelligent Electronic Devices and the main communication services principles
- Program different IED and communication services
- Analyze and interpret real traffic data issue from the electrical network

The first item is evaluated through multiple-choice questions. This evaluation gathers twenty questions and accounts 25% of the final grade. This outcome is considered as achieved when students answer correctly at least 50% of the examination questions. Then, students should be able to identify components (sensors, protective relays and communication protocols), name them and describe their functions. The second outcome is evaluated continuously throughout the experimental labs described in this paper. This evaluation accounts for 50% of the final grade. Students are evaluated on the programming and the obtained results in groups of two or three. They are oriented to check their implementations by downloading and running them on the platform. The learners must then explain the steps taken to instructors. Finally, for the last outcome (25% of the final grade), they have to summarize and comment the results of their analyses.

VI. CONCLUSIONS AND PERSPECTIVES

This article proposes an original Smart Grid lab class as a new way to address one key issue of the complex and large concept of Smart Grid with experimental and theoretical approaches of interoperability. Students solve real-life examples related to the operation of a distribution and power substation network by using the Standard IEC-61850. The article focuses on a small part of this standard to teach the semantics of it by programming GOOSE services. Engineers who follow this course will be aware of the association between industrial devices and sensors in a real scenario. As a result of this course, about 87% percent of the students were able to autonomously develop, implement and test their own protection strategies in real life scenarios. Protection-related aspects were prioritized since these are central for the long-term operation of the grid. Nonetheless, further use-cases could be explored in the future, such as traffic modeling, interoperability of systems as well as other services and other standards.

VII. ACKNOWLEDGMENT

The authors thank Schneider Electric for the technical support and contribution and Dr Diego Pereira Botelho for his helpful advice and comments.

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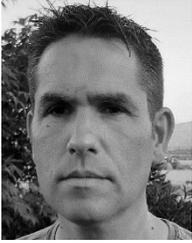
IX. BIOGRAPHIES

Antoine Labonne received the Master's degree in mechatronics from the University of Blaise Pascal, Aubiere, France, in 2005, and the Electrical Engineering Diploma from Grenoble Institute of Technology, Grenoble, France. Since 2005, he has been an Engineer at Grenoble INP doing his research at the G2Elab. His research interests have concerned the electrical network field, energy production systems, and renewable energy integration.



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