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An Original Smart-Grids Test Bed to Teach Feeder Automation Functions in a Distribution Grid

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Abstract—This paper proposes the description of an original Smart-Grids test bed aimed at teaching novel feeder automation functions to students from both university and industry origins. With this test bed, a lab class proposes to students first to develop feeder automation functions using scientific software and then to experiment by practically testing them on an emulated distribution grid platform, called PREDIS. This platform includes real medium voltage reduced scale loads, generators, and a supervisory control and data acquisition system. The presented lab class is part of a dedicated complete pedagogic module with lectures and experiments. Through the development, the tests and the deployments of their own solutions in an actual distribution grid, the students learn by doing from theory to practice the complete chain of Smart-Grids solutions: from the electrical to the communication layers.

Index Terms— Distribution grid optimization, education, experimental platform, feeder automation, Smart-Grids.

I. INTRODUCTION

Teaching the concept of “Smart-Grids” to students, not only in class, but with practical experiments, is a real challenge because it requires facilities with both electrical plus information and communication infrastructures. Nevertheless, future employers, like the Distribution System Operators (DSOs), the Transmission System Operators (TSOs), the balancing responsible parties, among others are interested to hire engineers or owners of a master’s degree with in-depth knowledge of Smart-Grids technologies. In this context, the very first questions that future employees are asked during their job interviews are aimed at exploring their understanding of the concept of Smart-Grids (general definition, actors and industry sectors concerned) and their practical sense on the matter. Of course, such answers can only come from what they have learnt during their studies. Furthermore, future employers expect students to be able to imagine new potential solutions and services for various grid actors, based on the deployment of new Information and Communication Technologies (ICT). This requires a system-of-systems way of thinking. Henceforth, the electrical engineering education institutions cannot rely only on the study of the grid components and their classical integration in a system, plus an

added short introduction to Smart-Grids based on general definitions proposed for example by government agencies. From our point of view, students need to experiment the concept of Smart-Grids lab classes, in order to better understand the technical challenges and the industrial potential of these recent concepts in terms of developments and services.

Previous studies have already pointed out the necessity for the electrical engineering education institutions to evolve and to propose online or face-to-face curricula dedicated to Smart-Grids [1-3]. The typical courses in this field are based on a multidisciplinary approach using mainly lectures and simulations. They aim at introducing additional skills related to new energy devices communication technologies, cyber-security [4], and market mechanisms. For example, [5-6] go further into details by describing each course modules of their Master program. [7] presents a co-simulation platform to couple the electric grid with its power components and communication and automation layers. Other courses focus on one particular function related to Smart-Grids and aim at including some experimental parts in their curriculum. For instance, [8] proposes that students focus on the design of protective relays and on their communication protocol with the substation. This course is based on simulations, intelligent devices, and associated communication systems. Another more complex test bed, aimed at illustrating the impact of electric vehicles on power quality, has been proposed in [9]. This test bench is equipped with a transformer (three possible power levels), a line (three possible lengths), electric vehicle chargers, inverters, capacitor banks, and a Supervisory Control And Data Acquisition (SCADA) system. In [10], an entire test bed is dedicated to intelligent electronic devices coupled with a power systems simulator in order to study aspects related to metering, protection, control, monitoring, and communication. Finally, [11] focuses on the study of the islanding mode of a Smart-Grid, thanks to a test bed consisting of two synchronous machines, active and reactive power loads, and a SCADA system. The main observation to be made regarding these examples is that all the courses in this field usually focus only on a part of the Smart-Grids chain, simulated with different kinds of software applications. This article describes a global approach to teaching Smart-Grids in the form of a lab class based on theory and practice on an experimental platform called PREDIS (French acronym for PROduction of Energy

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DIStributed) developed in the framework of the European project INTEGRAL in 2007 [12]. In this lab class, all the devices (electrical, communication, and information) are not simulated but actual or reduced-scale components (we are talking then about emulation and not simulation). Many concepts are illustrated with the help of the PREDIS platform.

This paper focuses on teaching students one of the major issues in the development of Smart-Grids: the active grid management for the mitigation of renewable energy impacts. With this objective, students develop and conduct experiments on feeder automation functions. This lab class belongs to a pedagogical course named “Micro-Grids, Smart-Grids and Super-Grids” that represents five ECTS credits for 60 hours of lectures (32h), tutorials (8h), simulations and experiments (20h). It addresses about 50 students in their last year of Master’s degrees in the Energy Department of the ENSE3 (French acronym for National School of Energy Water and Environment) engineering school and is available through three different curriculums. The first degree focuses on power systems, the second one on Smart-Grids and buildings, and the last one on energy systems and markets. All the students are more or less trained to the modelling and computations of the power system and their components depending on their curriculum. This course is also opened to students coming from other universities provided they have skills on power systems analysis (modelling of the power system components and load flows calculation). The lab class is divided into three parts, for a total of 12 to 16 hours. Before starting this lab class, 12 hours of general lectures are provided to students around the concepts of smart grids and focussing on feeder automation functions. Real on-going projects handled by academic and industrial partners are used to illustrate this lecture. An additional training using both lectures (10 hours) and simulations (4 hours) give them some skills on optimization modelling and methods which are necessary for the development of feeder automation functions. The PREDIS test bench is presented as the studied case where students will work. Finally 12 hours of mixt lectures and debates completed by 10 hours of simulations focused on dynamic studies and stability issues but are not detailed in this paper. Students are evaluated through an individual 2 hours exam which tests the technical skills they acquire during the module. In addition, their ability to solve a technical problem within working groups and to communicate its solution to a third person (not necessarily a specialist of the topic) is evaluated through reports for various labs and an oral defense. Section VI describes more in details the deliverables concerning the labs.

Section II describes the lab class and its general purpose, including the feeder automation functions developed. Section III describes more in details the experimental set-up allowing us to illustrate to the students the transition from theory to practice. This section should help colleagues to work on a similar test bed in their institutions. Section IV and V describe the results (from theory to practice) obtained during the lab class and the main conclusions learnt by students. The educational outcomes associated with the presented work will be analysed in section VI and finally the last section will give

a general conclusions and some perspectives to the future development of this lab class.

II. A SMART-GRIDS ORIENTED LAB CLASS

The proposed Smart-Grids lab class aims at studying feeder automation functions to solve, in steady state, current and voltage constraints created by the connection of Distributed Generations (DGs) to a distribution grid. The constraints are defined as a maximal admissible current and a range of voltage at every node within $\pm 5\%$ of the nominal voltage. Different numbers, locations, and types of DGs are integrated to the distribution grid through the definition of three scenarios. The feeder automation functions are presented as an alternative to a classical reinforcement of the grid. Indeed, as the renewable production is variable, these constraints could only appear a few hours per year. In this context, the reinforcement could be very expensive, limited, and non-optimal regarding the expected evolution of DGs in the future.

Considering a given distribution grid, students are asked to conduct load flows over a full year with an hourly time step for three scenarios considering multiple locations and types of DGs. The objective is for students to understand that the occurrence of a voltage or current constraint depends both on the type of production connected to the grid (wind or solar for example), and also on the features of the grid itself, for example long lines and reduced consumption (rural grids), short lines and significant consumption values (urban grids), and constant consumption, active and reactive powers (industrial grids). If there are any constraints, students first try to solve them using the On-Load Tap Changer (OLTC) of the substations. If there are remaining constraints, two other feeder automation functions are implemented then used: reconfiguration and Volt VAR Control (VVC).

The first part of the lab class is based on the OLTC. Students perform simulations using a graphical user interface that is provided. They have to find the optimal settings (the voltage target at the secondary of the transformer of the substation) in order to solve constraints when they appear in the grid.

The second part of the lab class consists in understanding, developing, and testing the reconfiguration (described in subsection II.A) and the VVC (described in subsection II.B) in order to solve automatically the constraints unsolved by the OLTC. In these parts, students develop their own high level code for the feeder automation functions, helped by some simplified synoptic and oral guidance. When debugged, the developed codes are inserted in the graphical user interface for a more dedicated work on testing the DGs integration scenarios. Finally, in the third part, the reconfiguration and the VVC functions are directly applied on a distribution grid belonging to the PREDIS experimental platform. The objective is to validate the results obtained through simulation and also to discuss their limitations. Indeed, it is essential to always recall to students the fundamental differences between simulations and real life. At the end of this lab class, students are capable:

- to handle some technical and economic issues related to the concept of Smart-Grids and to give examples of on-

going projects,

- to be aware of their impact on the distribution grid,
- to master some feeder automation functions such as voltage control and reconfiguration,
- to model cyber-physical systems grids concepts,
- to master optimization modelling and methods on several cases studied, chosen to be as close as possible to current industrial issues.

A. Feeder Automation Function No. 1: Reconfiguration

The French distribution grid is actually looped but radially operated thanks to the presence of Normally Open (NO) switches. In case of faults, the reconfiguration of the grid is enabled to reenergize customers while the fault is being cleared. We then speak about “reconfiguration during fault condition”. The principle of grid reconfiguration in normal mode is based on the fact that over-currents or voltage constraints depend on the way powers flow in the grid. The position of NO switches can balance power flows when over-currents or over-voltages appear or increase them when low-voltages appear. Many academic papers propose algorithms to find the best configuration that satisfies various objectives [13–18]. The idea in this lab class is not to propose the best one but to choose an efficient one that runs fast enough and is easy to implement by the students. For that purpose, the Sequential Opening Branch (SOB) has been chosen. It was first developed by Merlin and Back in 1975 based on a DC load flow [19] and then improved by Shirmohammadi in 1989 [20] by using an AC load flow. SOB is a greedy algorithm because, once a decision has been made in a given iteration, it will never be reconsidered in the next iterations. The SOB algorithm is based on the general link between power losses, currents, and voltages given by equations (1) and (2).

$$P_{losses} = 3RI^2 \quad (1)$$

$$P_{losses} = R \left(\frac{P^2 + Q^2}{V^2} \right) \quad (2)$$

With:

- R: line resistances (Ω);
- I: currents through the lines (A);
- P and Q: active and reactive power consumed by loads (W and VAR);
- V: voltage at the loads (V).

Decreasing power losses will decrease currents and increase voltages. The voltage profile will be more homogeneous and easier to regulate with the OLTC.

The configuration with the lowest power losses is the meshed configuration if no production is connected (all the NO switches are closed). The principle of the algorithm is then to start from the meshed grid. After a load flow, the line with the lowest current is the first to be opened if it does not prevent consumers from accessing electricity (i.e. no isolated node is created by opening the line). By doing so, the power losses of the meshed grid minus one line will be the closest to the power losses of the entire meshed grid. This procedure is iteratively repeated until the grid is radial.

B. Feeder Automation Function No. 2: VVC

The VVC optimization problem can be formulated with equations (3), (4), (5), and (6). It consists in finding the optimal settings for the secondary transformers voltages (V_1 to V_r) and the minimal amount of reactive power (Q_1 to Q_p) that DGs have to inject or absorb in the power grid without violating voltage and current limitations. Indeed, the circulation of reactive power flows tends to increase power losses and thus the operational expenditure of the DSO.

$$\min_H \sum_{k=r+1}^{r+p} H(k)^2 \quad (3)$$

$$H = [V_1 \ \dots \ V_r \ Q_1 \ \dots \ Q_p]^T \quad (4)$$

$$V_{min} \leq V_i \leq V_{max}, i = 1, \dots, n \quad (5)$$

$$I_j \leq I_{max}, j = 1, \dots, m \quad (6)$$

Where:

- r: number of OLTCs;
- p: number of DGs participating in the VVC;
- n: number of MV/LV substations;
- m: number of lines;
- V_1 to V_r : voltage references of the OLTC at the secondary of the HV/MV substations;
- V_r to V_n : voltages in the other nodes of the grid;
- Q_1 to Q_p : reactive power produced (if negative) or absorbed (if positive) by the DGs.

Many research papers propose algorithms to solve the VVC problem [21–23]. To simplify the optimization problem, it is supposed that both voltages at the secondary of the HV/MV transformers and the reactive power provided by DGs are continuous variables. Thus, the optimization problem is a nonlinear multi-variable problem with a set of constraints. For practical reasons, the students use the *fmincon* function from the Optimization Toolbox of Matlab [24] to solve it.

III. THE EXPERIMENTAL PLATFORM USED IN THE LAB CLASS

A. Context of development

The experimental platform used for this lab class is part of an institutional set of platforms called PREDIS. Its development started in 2005 with an initial budget of 7.4 M€. It is a demonstration tool on the intelligent management of energy, consisting of two reduced-scale grids (an industrial one and a distribution one), a dispatching platform, decentralized production, a real-time hybrid Power Hardware in the Loop (PHL) simulator, and a monitoring and intelligent building platform. Being used both for teaching and research, the PREDIS platform is also part of DERlab (European Distributed Energy Resources Laboratories) [25]. The distribution grid part of PREDIS was initially created to test self-healing solutions for distribution grids in the INTEGRAL project [12]. Since then, it has constantly evolved to illustrate Smart-Grids technologies based on the knowledge triangle principle (research–industry–education).

This paper focuses on the part of this platform proposing a reduced-scale distribution grid. The reduced-scale grid can be managed by the SCADA system developed in the Grenoble

Electrical Engineering Laboratory (G2Elab) [26] based on PcVue [27] and depicted in Fig. 1.

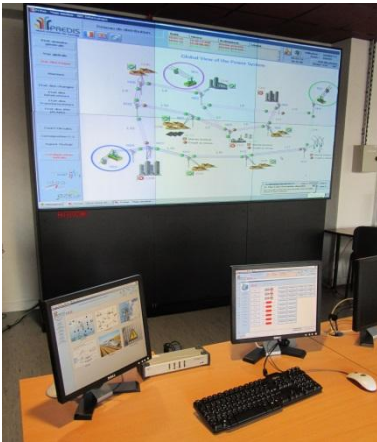


Fig. 1. PcVue SCADA system used for controlling the PREDIS distribution grid.

B. Description of the test bed components

In this subsection, we propose the complete description of the electric system, i.e. all components needed in order to make that platform operational. The objective is that, based on this data, others can find ideas to help develop their own test beds. By the way, these specifications are required since the students perform both simulations and experiments on them.

The PREDIS distribution grid is composed of more than 10,000 real connection points, around 500 switches, 4 industrial Programmable Logic Controllers (PLCs) with 300 I/O, 130 power measurements, current and voltage sensors, 10 fault location indicators, and a fault recorder plus an associated Object Linking and Embedding (OLE) for Process Control (OPC) server per substation

The experimental distribution grid emulates, at reduced scale ($S_{\text{base PREDIS}} = 30 \text{ kVA}$ and $U_{\text{base PREDIS}} = 400 \text{ V}$), the behaviour of an actual part of a French distribution grid ($S_{\text{base REAL}} = 30 \text{ MVA}$ and $U_{\text{base REAL}} = 20 \text{ kV}$). It consists of three different HV/MV substations, three types of consumption areas representing a total consumption of 30 MVA (with rural, urban, and industrial characteristics) and 27.25 MW of equivalent production. A graphical representation of the distribution grid is given in Fig. 2 (in radial operation mode) with all the locations of the available loads and generators.

For generators 3 and 4, two connexion locations are possible. These elements are described in detail in the next part. Each line is equipped with two switches at its start and end nodes. In Fig. 2, the dotted lines have one switch opened to ensure a radial operation of the grid. Depending on which line is opened, the radial architecture of the grid changes. In the PREDIS grid, the initial configuration of the grid is [8, 10, 12, 13, 17], meaning that lines 8, 10, 12, 13 and 17 are opened.

1) Loads

Nine loads can be connected to the distribution grid. Table I summarizes the characteristics of these loads.

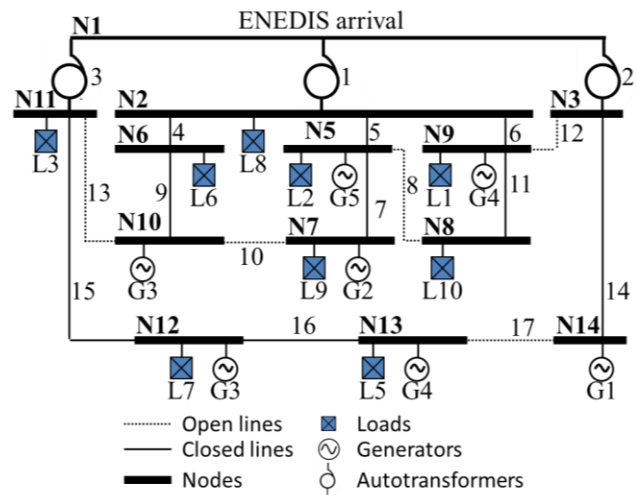


Fig. 2. The PREDIS distribution grid (initial configuration).

TABLE I
Characteristics of the loads

Load	Node	Type	Active Power	Comments
L1	N9	Induction machines	7.5 kW	– Induction machine, without variable speed controller. – Resistive torque applied by a direct current machine and its reversible thyristor controller (DMV 2342).
L3	N11		4 kW	
L2	N5		4 kW	
L5	N13	Resistor bench	1 kW	– Equipped with dimmers to remotely change the value of the resistance but harmonics will alter the quality of the voltage signal.
L6	N6			
L7	N12			
L8	N2			
L9	N7			
L10	N8	6 kW		

As an illustration, Fig. 3 shows one of the induction machines (tagged “1” in the figure) and the variable speed device associated with the direct current machine, which operates as a mechanical load (tagged “2” in the figure). Fig. 4 shows some of the resistive three-phase loads.



Fig. 3. An Induction machine used as a load.



Fig. 4. Resistive loads.

2) Generators

Five generators, representing DGs, can be connected to the distribution grid. Table II summarizes the characteristics of these generators. When generators are connected to the grid, the active and reactive powers can be controlled, using torque

control and the excitation current of the synchronous generator respectively. As an illustration, Fig. 5 shows the generator G4 (tagged “1” in the figure) with its power supply. In this figure, we can see the converter used for the torque control (tagged “6”), which is associated with an induction machine mechanically coupled to the synchronous machine upfront.

TABLE II
Characteristics of the generators

DG	Node	Type	Apparent Power	Comments
G1	N14	Synchronous machines with separate excitation (tagged “1” in Fig. 5)	13 kVA	Induction machines are used to control the generator to 1500 rpm. The control of the excitation (tagged “2” in Fig. 5) can be used for manually coupling the synchronous machine to the grid, with the help of voltage measurements at the terminals of the generator (tagged “3” in Fig. 5) and at the grid node (tagged “4” in Fig. 5). Otherwise, a synchro-coupler (tagged “5” in Fig. 5) can be used for automatic coupling.
G2	N7		2.5 kVA	
G3	N10 or 12		5.5 kVA	
G4	N9 or 13		5.5 kVA	
G5	N5		2.5 kVA	

3) Autotransformers

Fig. 6 shows the three autotransformers emulating the three HV/MV substations of the real grid. Their secondary is controllable to simulate a real OLTC.

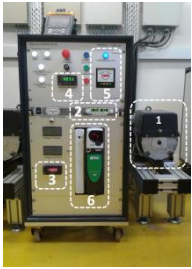


Fig. 5. A generator and its control.



Fig. 6. The three autotransformers emulating substations with OLTC.

4) Lines

Lines are modelled by their equivalent short line model with a resistance and a reactance in series as depicted in Fig. 7. The capacitive effect was not modelled because the equivalent value at such a low voltage is negligible. Equations (7) and (8) propose the expression used to represent the physical characteristics of the real grid (resistance and reactance) with the characteristics of the emulated one. The objective is to ensure a similar behaviour between both grids in the described test scenarios [28].

$$R_{PREDIS} = R_{REAL} \times \frac{\mu^2}{\gamma} \quad (7)$$

$$X_{PREDIS} = X_{REAL} \times \frac{\mu^2}{\gamma} \quad (8)$$

$$\mu = \frac{U_{base PREDIS}}{U_{base REAL}} = \frac{400}{20000} = 0.02 \quad (9)$$

$$\gamma = \frac{S_{base PREDIS}}{S_{base REAL}} = \frac{30 \times 10^3}{30 \times 10^6} = \frac{1}{1000} \quad (10)$$

with:

- R_{PREDIS} : resistances in the PREDIS distribution grid (Ω);
- X_{PREDIS} : reactances in the PREDIS distribution grid (Ω);
- R_{REAL} : resistances in the real distribution grid (Ω);
- X_{REAL} : reactances in the real distribution grid (Ω).

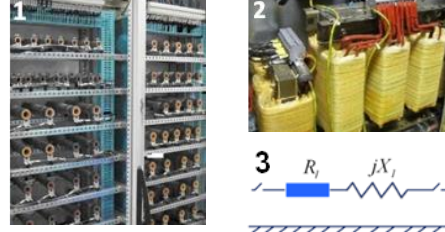


Fig. 7. Lines as emulated in the experimental distribution grid (resistance tagged “1”, reactance tagged “2” and the electric model tagged “3”).

Table III gives the value of the impedances used in the PREDIS Distribution grid for the lines.

TABLE III
Characteristics of Lines used to emulate Real Conductors.

Topology			Real grid		PREDIS	
Line	Start node	End node	Type	L (km)	R(Ω)	X(Ω)
1	N1	N2	Autotransformer		0.00	4.27
2	N1	N3	Autotransformer		0.00	8.53
3	N1	N11	Autotransformer		0.00	8.53
4	N2	N6	Almelec 148 mm ²	10	1.13	1.40
5	N2	N5	HN33S23 240 mm ²	8	0.6	0.35
6	N2	N9	HN33S23 150 mm ²	20	2.91	0.94
7	N5	N7	Almelec 54 mm ²	5	1.88	0.70
8	N5	N8	Almelec 54 mm ²	4	0.94	0.56
9	N6	N10	Almelec 148 mm ²	1	0.00	0.14
10	N10	N7	Almelec 54 mm ²	1	0.25	0.14
11	N9	N8	Almelec 54 mm ²	4	0.94	0.56
12	N3	N9	HN33S23 150 mm ²	1	0.11	0.05
13	N10	N11	HN33S23 95 mm ²	0.5	0.10	0.03
14	N3	N14	HN33S23 95 mm ²	5	0.5	0.25
15	N11	N12	Almelec 148 mm ²	30	2.6	4.2
16	N12	N13	Almelec 148 mm ²	30	3.12	4.20
17	N13	N14	Almelec 148 mm ²	10	0.94	1.4

5) SCADA, Communication, and Instrumentation Tools

The SCADA system ensures the management and control of the different elements of the PREDIS distribution grid, and also allows the display of various types of information provided by the measurement devices. The SCADA system is supported by a massive communication infrastructure and many measurement devices. The simplified ICT architecture designed to demonstrate the effectiveness of feeder automation functions during this lecture is shown in Fig. 8. Note that only the communication and instrumentation tools involved in this lab class are depicted.

All devices are linked using communication protocols such as the Modbus TCP/IP, IEC 60870-104, or IEC 61850 standards. The monitoring of power meters and the fault

passage indicators are transmitted to the PLC. There is one PLC per transformer/substation controlling the state of switches and the different measurements coming from the current and voltage sensors of lines and nodes directly connected to the transformer. A fourth PLC is dedicated to the surrounding environment of the grid, in our case to the loads and generators. Each PLC communicates with the SCADA system through an Ethernet TCP/IP connection. The feeder automation functions designed during this course are implemented within a real time Matlab control system using OPC to exchange data between the SCADA system and the software application.

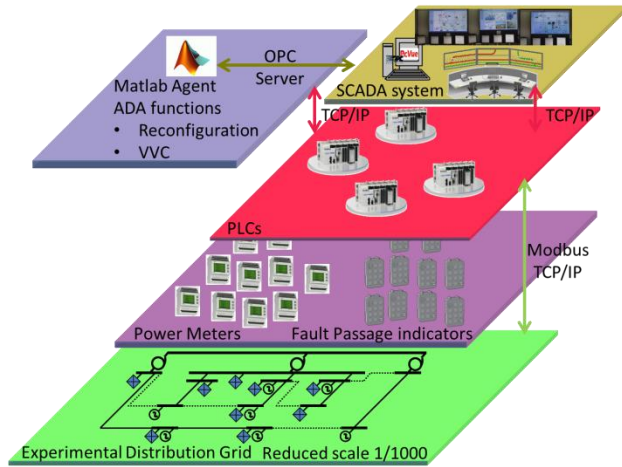


Fig. 8. Simplified ICT architecture of PREDIS distribution grid.

IV. SIMULATIONS ON THE PREDIS DISTRIBUTION GRID

A. Scenarios and Cases Studied

In order to have cases that are easy to test and to interpret by students, not all the available loads and generators of the actual PREDIS system are used. Fig. 9 provides the schematic of the grid in the initial configuration (lines 8, 10, 12, 13, 17 open) showing the location of loads and the possible locations of generators. To help the reader see the different configurations found through the paper, only the net radial diagrams will be provided in the next sections (without the representation of opened lines).

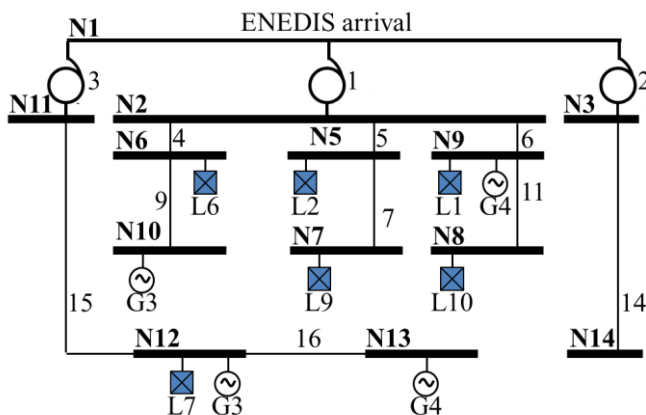


Fig. 9. Case studied in the lab class with the initial configuration

In the simulation part, the real distribution network is actually studied considering power inputs of loads and generations in MW under a voltage level of 20 kV. These values are then converted in Per-Units values. The different variables of the real network and the PREDIS network are equal in Per-Units as equations (7 - 10) are used. Then, if students want to check their conclusion by experimenting some test cases on the PREDIS platform, they just have to multiply the variables by the PREDIS base values.

The loads considered in this lab class are L_1 and L_2 , which simulate two industrial consumers, and L_6 , L_7 , L_9 , and L_{10} , which simulate four residential consumers. The maximal consumption of the industrial loads is set to 3 MW with a power factor of 0.93 and the maximal value of the consumption of the residential loads is set to 1 MW. Two producers, G_3 and G_4 , respectively, can produce a maximum of 4.7 MW and will emulate photovoltaic (PV) generators.

Students test the influence of the number of DGs by connecting G_4 to N_{13} (scenario 1) and both G_4 to N_{13} and G_3 to N_{12} (scenario 2). They will also test the influence of the location of the DG by connecting G_4 to N_9 instead of N_{13} (scenario 3). Fig. 10 shows the normalized profile of a residential consumer and a PV production used in this lab class. The consumption profile has been inspired from data available on the ENEDIS (main French DSO) website [29] and the PV production from data available on the RTE (French TSO) website [30]. Both of them correspond to a day in August because it allows a sufficient disparity in the results for pedagogical purposes. Five time steps have been identified (3:00 am, 12:00 am, 1:00 pm, 4:00 pm, and 9:00 pm), corresponding to local minimums or maximums of consumption and generation. The industrial loads are supposed to consume their constant power between 3:00 am and 9:00 pm so they are not represented in Fig. 10.

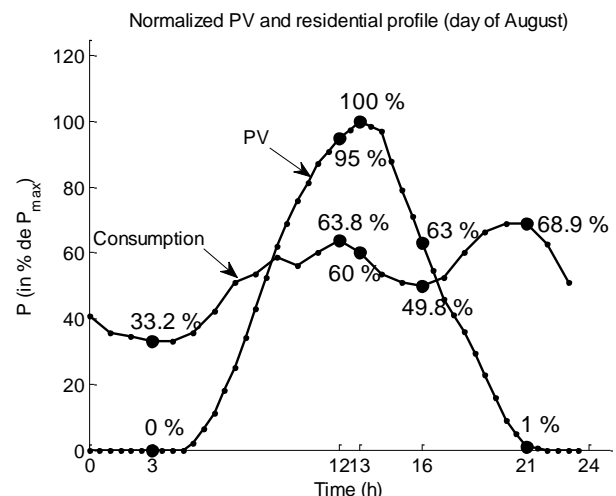


Fig. 10. Normalized residential consumption and PV profile during a sunny day of August.

B. Using Feeder Automation Functions to Solve Constraints

1) Using only the OLTC

First, students try to meet technical constraints when they appear (currents and voltages) using the OLTC of the HV/MV substations for the three previously described scenarios. S1,

S2 and S3 will be respectively used for scenario 1, 2 and 3 in the rest of the text. Due to the radial operation of the distribution grid, S1 and S2 impact the feeder of the third substation containing N11, N12 and N13 (see Fig. 9). Fig. 11 shows the voltages of these three nodes for the 5 time steps.

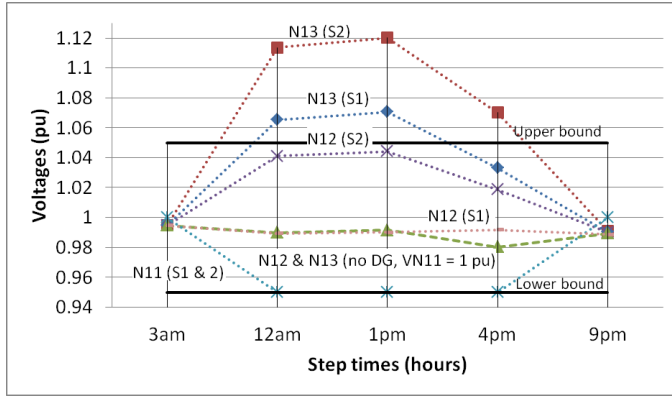


Fig. 11. Voltage profiles for the constrained nodes.

The best voltage setting of N11 has been chosen so as to minimize the voltage constraints. When the production is low (03:00 am and 9:00 pm), N11 is set to 1 pu and when the production is high (12:00 am, 1:00 pm and 4:00 pm), it is decreased until the minimal admissible value of 0.95 pu. It can be seen that if G4 is connected to N13 (S1), the voltage profile cannot be respected every time for N13 (1.065 pu at 12:00 am and 1.07 at 1:00 pm). Adding a generator at N12 (S2) worsens the situation (N13 reaches 1.12 pu at 1:00 pm) and creates an additional violation at the time step of 4:00 pm. These periods of constraints where the use of OLTC is insufficient correspond to periods of high production. There is no current constraint because the lines are oversized regarding the power flows circulating in the lines. In the worst case (S2 at 1:00 pm), the current in line 15 is 64.5% of the maximal admissible current. In the case of S3 (G4 connected to N9), no voltage or current constraints appear in the grid. The explanation is the location of N9, in the industrial zone of the distribution grid. The DGs have a positive impact on the voltage profiles of the grid.

To conclude this part, changing the OLTC secondary settings does not allow respecting the voltage constraints at 12:00 am and 1:00 pm for S1 and S2 and at 4:00 pm for S2. Reconfiguration and VVC will be applied in these cases.

2) Using Reconfiguration

After implementing the reconfiguration algorithm, students should obtain a vector of five values that are the five lines to open (starting from the meshed distribution grid) in order to minimize the constraints in a radial operation. The configuration found by the SOB method for S1 (G4 connected to N13) at the constrained time steps of 12:00 am and 1:00 pm is [4, 6, 7, 8, 15], as depicted in Fig. 12.

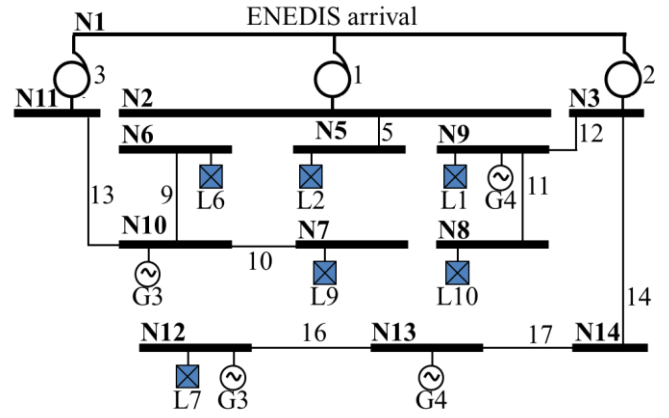


Fig. 12: Configuration found for S1 (lines [4, 6, 7, 8, 15] opened).

If G3 is added at N12 (S2), then the configuration found for 12:00 am, 1:00 pm, and 4:00 pm is [4, 6, 7, 8, 16], as depicted in Fig. 13.

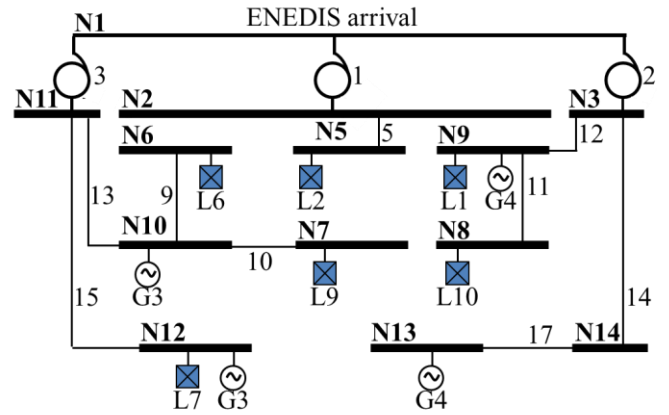


Fig. 13: Configuration found for S2 (lines [4, 6, 7, 8, 16] opened).

Changing the configuration decreases the lifetime of NO switches. Indeed, they have an electrical lifetime of about 6000 operations. So, finding one configuration that suits the entire day would be less expensive in the long run. This is the last exercise in this section that is proposed to the students, who are asked to search for a sub-optimal configuration, able to cope with an entire day, or the maximum number of scenarios. The conclusion of this part is that in the configuration [4, 6, 7, 8, 16] of Fig. 13, the constraints are respected all day long for the three scenarios. Thus, this configuration will be the optimal one for the entire day.

3) Using VVC and the OLTC

Table IV shows the results obtained when VVC is applied only to the time steps for which the constraints are not solved with the OLTC. The French DSO actually imposes on producers (based on a power threshold) that the reactive power produced should range between $-0.35 \times P_{max}$ and $0.4 \times P_{max}$. In this example, as P_{max} is 4.7 MW, Q must be between -1.645 and 1.88 MVAR. This constraint is respected in all cases.

TABLE IV
VVC Solutions for the Studied Scenarios and Step Times.

Time step	S1 (G4 at N13)		S2 (G3 at N12 & G4 at N13)	
	Q(pu)	OLTC settings [V ₁ , V ₂ , V ₃] (pu)	Q(pu)	OLTC settings [V ₁ , V ₂ , V ₃] (pu)
12:00 am	Q _{G4} = -0.286	[1.025, 1, 0.95]	Q _{G3} = -0.473 Q _{G4} = -0.926	[1.025, 1, 0.95]
1:00 pm	Q _{G4} = -0.381		Q _{G3} = -0.517 Q _{G4} = -1.009	
4:00 pm	Not computed because there are no voltage constraints		Q _{G3} = -0.156 Q _{G4} = -0.308	[1.023, 0.999, 0.95]

C. Conclusions on the Simulation Part

In this simulation part, students develop two blocks of code to find the best reconfiguration and VVC solutions for a given scenario. Then, they implement them in a pre-coded graphical user interface to run different scenarios of DGs integration at different times of the day. At the end of this part, students are able to understand the difficulty of coding feeder automation functions for grids. Also, they understand the impact of the location of the DGs integration in the grid (either in a rural, an industrial or an urban area). Finally, they see the impact of the time of the day on the loads and productions curves, which will further have an impact on the remaining constraints in the grid after a load flow.

V. EXPERIMENTS ON THE PREDIS DISTRIBUTION GRID

As the simulation is not real life, the second part of this lab class expects from the students that they test some of their functions on the PREDIS distribution grid. Exploring all the 5 time steps of the three scenarios for the three solutions (OLTC, reconfiguration and VVC) would lead to 45 sets of experiments. As there are between 15 and 20 students per lab class session and only 5 of them can practice with the PREDIS platform at the same time, all these 45 experiments cannot be done. Consequently, it has been proposed to students to test the three previous scenarios for the worst case of the day (1:00 pm). As depicted in Fig. 10, at 1:00 pm, the residential loads are consuming 0.6 MW, which represents 60% of their maximal consumption value, and the industrial loads are at their maximal consumption value (3 MW). The industrial loads are emulated by induction machines and the residential loads by a resistor bench. Their consumption is set respectively to 3 kW and 600 W (considering the scale between the actual grid and the PREDIS one). The measurements at the generators nodes, the resistors, and the secondary of the autotransformers are readable remotely using the SCADA system. The objective is for the students to compare these measurements to their simulation results and validate (or not) their functions.

A. S1: G4 Connected to N13

1) Using only the OLTC

After the different loads and generators have been started up, the voltage at the secondary of the autotransformers is adjusted to optimize the voltage profile. Fig. 14 and Fig. 15 present screenshots of the available monitoring of the loads, generators, and autotransformers given by the SCADA

system.

The voltages of the generators are monitored directly at their connection nodes, even if they are not actually producing energy. For example, the voltage of G3 is measured at N10. The devices used to measure the power flows are wired in the same way for generators and for loads; thus only the sign indicates the direction of the power flow.

	Load 1	Load 2	Generator 3	Generator 4
P	3.230 kW	3.230 kW	0.000 kW	- 4.680 kW
Q	0.460 kVAr	0.660 kVAr	0.000 kVAr	- 0.03 kVAr
U12	387 V	409 V	416.59 V	427.59 V
U23	388 V	410 V	416.49 V	427.09 V
U13	388 V	411 V	417.79 V	427.69 V

Fig. 14. Available measures for loads and generators.

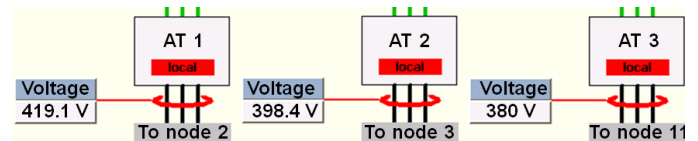


Fig. 15. Available measures for autotransformers as proposed by PCVue.

a) Definition of simulation case a: measurements inputs

Some differences prevent the students to emulate with the PREDIS grid what they have been doing in simulation. It can be noticed that the power factor of the induction machine is very good (close to unity) compared to the hypothesis of 0.93 formulated in the simulation part. Indeed, in real life, the induction machines do not behave as a constant PQ load. For residential loads, the measured power is 600 W for all loads except load 10, where $P_{L10} = 800$ W. In fact, for load 10, the step of power of the resistor bench is quite large (400 W). For this reason, it is not easy to apply exactly 600 W.

As G4 is connected to N13, it causes a significant over-voltage. Then the secondary of the autotransformer to which it is connected decreases to 380 V (the lowest admissible voltage, corresponding to 95% of 400 V). It can be noticed that even with this action, the voltage of N13 is still around 427 V and is thus higher than the admissible limit of 420 V. In another part of the grid, the voltage at the secondary of autotransformer 1 is increased to its maximum value in order to act on the voltage profile of N9. Indeed, the industrial loads are causing a voltage drop. For all these reasons, simulations are run once again with the new measured inputs. This will be called simulation case a.

b) Definition of simulation case b: hypothetical inputs

In actual distribution grids, there are no measurements at the MV/LV transformers. DSOs perform their studies under a set of hypotheses formulated from historical data and prediction methods. By applying these hypotheses to our case study, the only available information would be that L1 and L2 are consuming 3 kW and 1.2 kVAR and that L6, L7, L9, and L10 are consuming 600 W. These hypothetical inputs have been considered in the simulation case b.

Table V compares the voltages measured during the experiment, the voltage obtained with the simulation case a, and the voltage obtained with the simulation case b. For N6, N7, N8, N12, N14, the voltages are not remotely measured. The objective here is to encourage the students, as future engineers, to reflect on their ability to reproduce the theory in reality, and also to loop back to the simulations whenever detecting deviations in experiments.

TABLE V
Experiment versus Simulation, only with OLTC, S1: G4 at N13.

OLTC settings: [419.1, 398.4, 380]							
Node	Experimental Voltages (in V)			Simulation case a (measurements inputs)		Simulation case b (hypotheses inputs)	
	Min	Max	Mean	Voltage (in V)	Err (%)	Voltage (in V)	Err (%)
N2	Not provided			419.1	0	419.1	0
N3	Not provided			398.4	0	398.4	0
N5	409.00	411.00	410.00	412.97	0.72	412.85	0.69
N9	387.00	388.00	387.67	387.65	0.00	389.28	0.42
N10	416.49	417.69	416.92	417.47	0.13	417.47	0.13
N11	Not provided			380	0	380	0
N13	427.09	427.69	427.46	428.67	0.28	428.20	0.17

Being imposed as the OLTC references, the voltages at N2, N3, and N11 are identical between the simulations and the experiments. The relative error between simulation and experiment for a given node N_i is computed with (11).

$$Err(N_i) = \frac{U_{simu}(N_i) - mean(U_{exp}(N_i))}{U_{simu}(N_i)} \times 100 \quad (11)$$

where:

- $U_{simu}(N_i)$: simulated voltage at N_i , (V);
- $U_{exp}(N_i)$: $[U_{i1} \ U_{i2} \ U_{i3}]^T$ = experimental measurement of voltage at N_i for phases 1, 2, and 3, (V).

It can be noticed that the error in case a is below 1%. The students can thus see that the provided model of the grid and the load flow algorithm lead to a good estimation of the steady state of the actual distribution grid.

In the second case (case b), the relative error increases only for N9 due to the reactive power of load 1. Nevertheless, the error remains below 1%. A small imbalance can also be noted between phases, reaching a maximum of 2 V for N5. As the range of the sensors precision is about 1%, it can be concluded that the difference between simulations and experiments may be due to this range of precision and to the phase imbalance in the PREDIS distribution grid.

2) Using Reconfiguration

In this part, students use their computed reconfigured topology, opening lines [4, 6, 7, 8, 15] of the distribution grid. Compared to the initial configuration, proposed in Fig. 13, four NO switches states have to be changed. The normal procedure for changing the configuration would be first to close the loop where the new NO switches are located and then to open the old loops. The problem is that this method creates a temporary loop between substations. This is not a

constraint if the two transformers of the loop have the same voltage (both in module and phase). On the PREDIS platform, the three autotransformers have different phase ratios. So, if two of them are looped, a high current could trigger the protection devices and destroy some equipment. For this reason, during the experiment, students first need to open the loop before changing the state of any NO switch. This action disconnects loads and shuts down production, which has to be started up again once the new configuration is set. Once again, through these procedures, reality hits the students, more used to instantaneous simulations. Table VI compares the simulations with the experiments. It can be noticed that the violation of voltage at N13 disappears. By the way, the voltage profile is better because the OLTCs are not as close to the margins as before.

TABLE VI
Experiment versus Simulation using reconfiguration, S1: G4 at N13.

OLTC settings: [400.9, 395, 404.1]					
Node	Experimental Voltages (in V)			Simulation	
	Min	Max	Mean	Voltage (in V)	Err (%)
N5	393.00	394.00	393.67	395.48	0.46
N9	390.00	392.00	391.00	393.80	0.71
N10	402.79	404.29	403.62	403.80	0.04
N13	417.29	418.99	418.16	416.65	0.36

3) Using VVC with the OLTC

In the considered case, running the VVC program provides a solution to meet the voltage constraints: G4 has to absorb 0.37 kVAR. Also, the settings of the autotransformers should be set to [418.9; 398; 380], as depicted in Table VII.

Students find almost the same results through simulations than with the experiment (0.38 kVAR, refer to Table IV), which is encouraging for this VVC function, already used by DSOs. Students also conclude that this VVC function is based on a centralized control, where a good knowledge of the grid, loads, and production is mandatory. It should be mentioned that in order to make this function operate correctly in an experimental environment, the voltage at the secondary side of the autotransformers should be as constant as possible, which is not always the case due to the practical connections to the local electricity provider. We encountered this problem while setting up this experiment, which, as a result, imposes a limitation on the duration of the experiment for the students.

TABLE VII
Experiment versus Simulation (VVC, G4 at N13).

OLTC settings: [418.9, 398.4, 380]					
Node	Experimental Voltages (in V)			Simulation	
	Min	Max	Mean	Voltage (in V)	Err (%)
N5	410.00	411.00	410.33	412.77	0.59
N9	388.00	389.00	388.33	387.17	0.30
N10	416.69	417.49	417.19	417.27	0.02
N13	417.99	418.79	418.46	419.77	0.31

The experiments have been described in detail only for the first scenario. For the two other scenarios, only the results are provided in order to validate the good operation of both the

simulations and the experiments.

B. S2: G4 connected to N13 and G3 connected to N12

This case is similar to S1 for the autotransformers 1 and 2 but a larger increase of the voltage in the area of the autotransformer 3 is expected because two DGs are located in its zone. The results using only OLTC are given in Table VIII.

TABLE VIII
Experiment versus Simulation using only OLTC, S2: G4 at N13 and G3 at N12.

OLTC settings: [418, 400.3, 380.1]					
Node	Experimental Voltages (in V)			Simulation	
	Min	Max	Mean	Voltage (in V)	Err (%)
N5	409.00	410.00	409.67	411.81	0.52
N9	387.00	389.00	388.00	386.43	0.41
N12	420.79	421.29	421.39	416.30	1.22
N13	444.29	445.19	444.82	444.92	0.02

An increased relative error (1.22%) can be observed for N12. This is a little higher than the sensor precision, so the model of line 12 may not be accurate enough. As an example, if the resistance of the line upstream N12 is increased by 2% and its reactance is decreased by 2%, the relative error becomes 0.86%. This is an illustration of the reality for students. Indeed, in actual distribution grids, the DSO knows the characteristics of their conductors but the values of the real resistance and reactance can vary depending on factors such as temperature or connection quality.

The VVC and reconfiguration results are summarized in Table IX. The experiment validates the simulation except for N12, where the relative error is also above 1%.

TABLE IX
Experiment versus Simulation with VVC and reconfiguration, S2: G4 at N13 and G3 at N12.

VVC: $Q_{G3} = -0.5$ kVAR & $Q_{G4} = -0.99$ kVAR					
OLTC settings: [416.4, 401.9, 380]					
Node	Experimental Voltages (in V)			Simulation	
	Min	Max	Mean	Voltage (in V)	Err (%)
N5	407.00	407.00	407.00	410.05	0.74
N9	385.00	386.00	385.33	385.17	0.04
N12	402.79	404.39	403.49	398.83	1.17
N13	417.49	418.99	418.19	418.7	0.12
Reconfiguration: [4, 6, 7, 8, 16]					
OLTC settings: [400.7, 391, 389.9]					
Node	Experimental Voltages (in V)			Simulation	
	Min	Max	Mean	Voltage (in V)	Err (%)
N5	393.00	394.00	393.67	395.35	0.43
N9	386.00	387.00	386.67	389.81	0.81
N12	417.59	418.99	418.12	413.91	1.02
N13	417.59	418.79	417.99	415.93	0.49

C. S3: G4 connected to N9

This scenario represents a connection of a DG in an industrial area. In this case, G4 does not cause technical constraints but even improves the voltage profile compared to the same case without production in the feeder where the

production is connected. In Table X, it can be seen that at N9, where the production is connected, the voltage difference with and without production is 36.9 V. Indeed, in N9 an industrial consumer causes a big voltage drop that can be solved by increasing the voltage at N2 using the OLTC. Setting the maximal value at N2 (420 V) increases the voltage at N9 to 385 V. With the production connected, there is no need to increase the voltage at the secondary: with 401 V at N2, we have 403 V at N9. The relative errors are good (below 1%).

TABLE X
Experiment versus Simulation, S3:G4 at N9.

OLTC settings: [400.7, 402.6, 402.1]						
Node	Experimental Voltages (in V)			Simulation		Simulation without G4
	Min	Max	Mean	Voltage (in V)	Err (%)	Voltage (in V)
N5	391.00	392.00	391.67	394.29	0.67	394.29
N9	399.69	400.09	399.86	402.86	0.75	366.08
N12	398.69	398.99	398.89	398.13	0.19	398.89

D. Conclusions on the Experimental Part

This experimental part enables students to learn by doing. First, they actually see the voltage decrease as a consequence of the consumption and the voltage increase when production is injected. Another interest of the experiments is to test what simulations cannot show: in real life, the DSO does not exactly know all the values of the components of their grid and some data can also be false (for example wrong parameters for a conductor in the database). Also, the sensors have a given precision to which we add the uncertainties on consumption and production predictions. Consequently, this raises awareness regarding the margins which ensure that the voltage remains between +/- 5 % of the nominal voltage. Thus, students can assess the uncertainties related to parameters and measurement errors. Finally, another major issue in the context of Smart-Grids that this experiment illustrates is the link with ICT. Students can encounter some devices not working properly or giving wrong information highlighting the necessity for the Smart-Grids solution to be robust in case of sensors failures. Students eventually learn that even if innovative solutions work during the simulations, they must be first tested in a demonstrator in order to have a feedback before implementing them in real life. This final conclusion makes the link between the lectures presenting the Smart-Grids on-going projects and the lab class described in this paper.

VI. EDUCATIONAL OUTCOMES

This lab class enables the students to achieve four main outcomes which would not be fully possible with other classical pedagogical approaches such as lectures or simulations only. At the end of the lab class, students will demonstrate their ability to:

- locate, differentiate and define all the regular and advanced power system devices of the Smart-Grids,
- calculate and apply the good settings to the different components of a power system in order to solve a technical constraints based on DSO regulations,
- rank various innovative Smart-grids solutions based on technical indicators and economic assumptions,

- create and perform a test case to illustrate an electrical engineering phenomenon based on a list of topics and safety guidelines.

The first outcome is evaluated through the individual exam mentioned in the introduction. Six questions on power systems components (from the sensor to the actuator including communication protocols) are provided to the students. They should be able to recognize a component, to name it or give its function and properties. The students have to answer correctly to at least 50% of the questions to validate this outcome.

To evaluate the second and third outcome, the students provide a report by group of 2 or 3 where they have to make a synthesis which compares some Smart-grids innovative solutions based on their simulations and experiments. Some rules are given to students for the structure of the report. First, they need to propose an introduction to the topic and its associated challenges. Then, they have to illustrate their analysis using simulation and experimental results (a list of results without any structure or comments will be penalized) and finally it is mandatory to add their thought on the added values of experimentation compared to simulation alone. A minimum score of 8/16 is required to validate these two outcomes.

Finally, the fourth outcome is evaluated through a one page synthesis where students have to present a test case, its simulation and experimental implementation. Two examples are the overcurrent creation when two transformers are looped and the desynchronization of production when their voltage increases too much. A minimum score of 2/4 is required to validate this outcome.

VII. CONCLUSION AND PERSPECTIVES

This article proposes a Smart-Grid lab class as a new way to address the complex and large concept of Smart-Grids not only with simulations but also with experiments. Students can practise on an emulated distribution grid that has the same behaviour in steady state condition as a real distribution grid. Three feeder automation functions are developed during the simulation and validated during the experiment (OLTC, reconfiguration and VVC) on three scenarios and multiple time steps. The objective is to give the opportunity to students to learn the impact on a grid of integrating the renewable production in a rural, industrial or urban area, and in addition, the impact of the time of the day (i.e. the correlation between loads and productions curves).

Currently, this lab class is presently being improved by developing other operational functions such as load and production curtailments. Also, an economic module is being developed under a set of hypotheses. Indeed, in addition to the electrical engineering and the ICT parts, the economics are an important step to be integrated in this lab class in order to complete a comprehensive vision on Smart-Grids. Finally, stochastic methods destined to deal with uncertainties on loads and generation will be added through the use of a probabilistic or possibilistic load flow.

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IX. BIOGRAPHIES

Marie-Cécile Alvarez-Herault (M'07) received her Engineering Diploma, her Master's Degree and her PhD in electrical engineering from the Grenoble INP, France, in 2007 and 2009. After a 6 months assignment for Schneider Electric, she joined Grenoble INP G2Elab, an electrical engineering laboratory in 2010 as an associate professor. Her research interest concerns the impact of Smart Grids flexibilities and uncertainties on the decision investment planning. She is currently hosted at the LBNL (Lawrence Berkeley National Laboratory) in California where she performs studies on the LV network observability for distribution network planning.



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Thierry Braconnier received his Licence degree (Electric Distribution and automatisms) from University Joseph Fourier in 2011. Since 2011, his research interests concern the electrical network field and energy production systems.



Vincent Debusschere (M'10) joined the Ecole Normale Supérieure de Cachan (ENS Cachan), Cachan, France, in 2001, for studies in the field of applied physics. He received a Masters degree in information, systems and technologies (IST) from University Paris-Sud XI and ENS Cachan, Orsay, France, in 2005, and the Ph.D. degree in ecodesign of electrical machines from ENS Cachan, in 2009. He joined the Grenoble Electrical Engineering Laboratory (G2Elab) from the Grenoble Institute of Technology, Grenoble INP, France, in 2010. His research interests include renewable energy integration, energy efficiency, flexibility levers for Smart grids, economical and environmental optimization and evaluation criteria.

Dr Raphael Caire (M'04) had been working in Power Electronic field, in USA at the Center of Power Electronic System (CPES) in 2000. He received his Ph. D. Degree from the Grenoble Institute of Technology (Grenoble InP) in 2004. During this PhD, his topics of research were the impacts and control of dispersed generation on distribution system. In 2004 and 2005, he worked as a post-doc researcher in the ElFER Institute in the University of Karlsruhe, Germany on technical aspects of Virtual Power Plant in distribution network. Between 2005 and 2006, he has been working with EDF R&D as a research engineer. Since 2006, he is an associate professor in Grenoble INP, doing his research part at the G2ELAB and his teaching duty at the Ecole Nationale Supérieure de l'Energie, de l'Eau et de l'Environnement. His recent works deal with new architectures of distribution networks, reconfiguration, protection and new power electronic devices to control power flows.



Nouredine Hadjsaid received PhD and the "Habilitation à Diriger des Recherches" degrees from the Grenoble Institute of Technology (Grenoble InP) in 1992 and 1998 respectively. He has served as an assistant professor at the Ecole Nationale Supérieure d'Ingénieurs Electriciens de Grenoble and the Laboratoire d'Electrotechnique de Grenoble from 1992 to 2000. He has been appointed as a full professor at the same Institute since 2000. He is presently the General Director of a common research center between EDF, Schneider Electric and INPGrenoble (IDEA) on distributed generation and future electrical distribution systems.

