Setup for HIL simulations of isolated microgrids at the Gridspertise LV Smart Grid Lab

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***Abstract*— Encouraged by the ongoing energy transition, the increasing widespread of the distributed energy sources (DERs) will become even more relevant in the next future, boosting the evolution of the distribution networks towards the smart grids concept. This change assumes further relevance if we consider the goal to improve the quality of the service, the need to be more customer-oriented and the increase of active actors operating on the grids over different levels. Operating the present distribution networks as smart grids requires a strong digitalization process, involving several components and functionalities, such as protection, control, automation and monitoring. The digital transformation is mainly accomplished by introducing Intelligent Electronic Devices (IEDs) whose conceptualization, design, testing and integration could be performed in suitably arranged laboratories. In this context, Gridspertise owns and operates two laboratories, located in Milano and Bari, in Italy, to perform research, development and testing activities on smart grids, on both Medium and Low voltage (MV and LV, respectively) levels. The paper focuses on the architecture that has been configured to control and automate isolated or weakly connected microgrids to enhance their stability and efficiency. Further, it provides a description of the main smart grid devices involved and how they have been integrated to operate in the real field conditions.**

Keywords—Smart Grids, Distribution Network Digitalization, Smart Grid Laboratories, Microgrid Controller

I. INTRODUCTION

E-distribuzione is the main Italian Distribution System Operator (DSO). The continuous research and development of innovative technological solutions are among the founding pillars of the company, that serves more than 31.5 million customers and manages about 1.100.000 km of the Italian electrical network. In the context of the smart grid innovation, E-distribuzione leverages on the services provided by Gridspertise, a new company of the Enel S.p.A. group, born in 2021 as a subsidiary of Enel Grids [1]. One of the main targets of Gridspertise is to boost the digitalization process of the distribution networks and consolidate the diffusion of the smart grids concept targeting markets in Europe, Latin America and North America, where Enel Group already has a strong presence, as well as Asia-Pacific region, where the investment in smart grids will drive infrastructure upgrade projects in the near future.

Recently, several countries all around the world look with confidence to the energy transition process. As a matter of fact, this process has received a significant boost due to several causes, as the registration of more and more frequent adverse climate events and, not least, by socio-political dynamics that push several countries to embrace the energy independence politics. The energy transition process involves several aspects of the energy production, distribution and utilization. Clearly, it also involves the electric power distribution networks. As a matter of fact, energy transition is led, among others, by the diffusion of distributed energy resource (DERs). To enable the present power grids to accept more and more DERs, they need to evolve towards the concept of smart grids.

Smart grids integrate aspects of electric and communication engineering and are indicated as a valid support to the diffusion of the renewable energy resources (RES) [2]-[5], as well as to the diffusion of the electric mobility, both targeting the reduction of the CO2 emissions and other air-polluting components. Additionally, another considerable result that could be achieved by implementing the smart grid concept is the better management of the power flows and demand peaks, which could reflect on the lesser need to install new generation units. Last but not least, customers can benefit from implementation of smart grids since the energy delivery service is more reliable and high quality labelled, as well as they could have a greater awareness of their consumption and could be encouraged to care about a rational use of the energy and even leaded to reduce, implicitly, the energy consumption.

The evolution of the distribution networks towards the smart grids requires a digital transformation. The latter

This publication reports results of the activities of the B88I17001020008-ISMI project within the National Operative Program (PON Grandi Progetti R&S - PON IC 2014/2020 "Agenda Digitale e Industria Sostenibile") funded by the Italian Ministry for the Economic Development (MISE).

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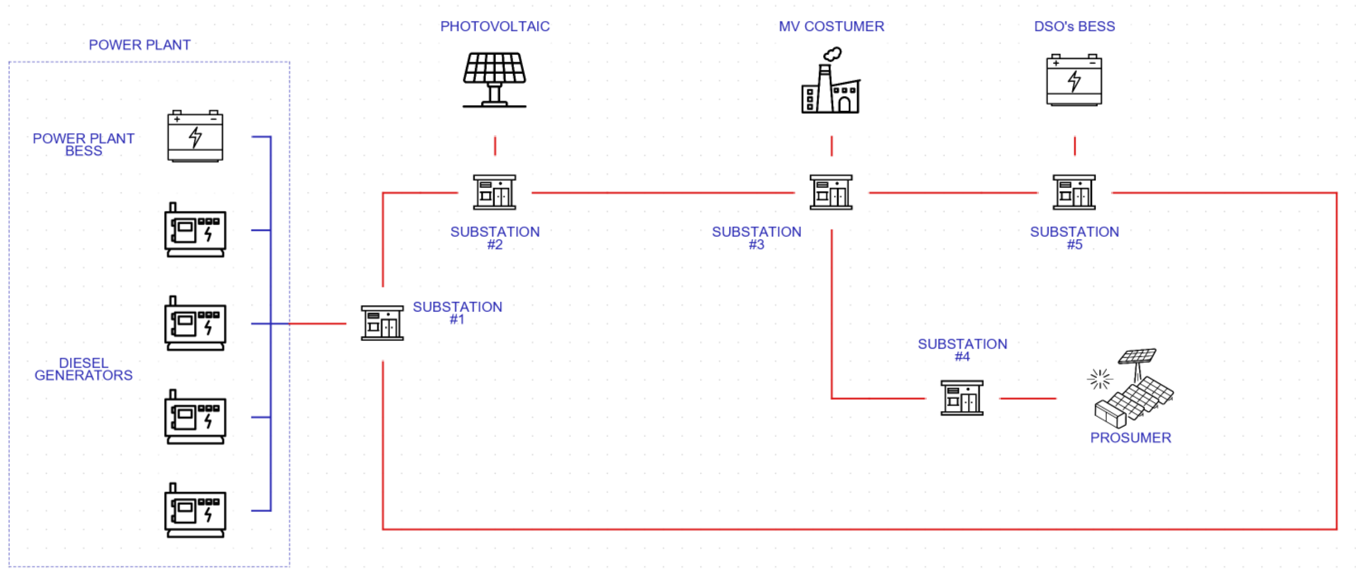

Fig. 1. Single-wire scheme of the simulated test microgrid.

consists in the introduction of intelligent electronics devices (IEDs) in several aspects related to the distribution networks, including protection, control, automation and monitoring. These devices, which mainly consist of hardware and software components, can communicate each other to exchange information and data, as well as execute commands and actions to operate a power grid as a smart grid. The interaction and interfacing between different, both functionality-wise and manufacturer-wise, IEDs operating protection, control and supervision functionalities of the distribution networks, have been favored by the introduction of the international standard IEC 61850.

Despite the introduction of standards, operating and orchestrating networks of IEDs is non-trivial and they need to be suitably configured and tested. These aspects are further relevant if we consider that any failure on the IEDs or in their communication will have impacts on the DSO costs, both tangible (e.g., non-delivery of the service) and intangible (e.g., loss of trust towards the final costumers). The possibility to have suitably arranged facilities to design, test and validate new IEDs, as well as perform their real field conditions of integration and operation, takes a particular relevance. As a matter of fact, it is possible to speed-up the various phases of the IEDs prototyping and field-deployment, to reduce the risk of malfunctioning and failures once they are installed in real field. This allows the DSO to target the delivery of a high-quality service. Finally, advanced laboratories provide a valuable mean to train operation and maintenance units.

In this frame, Gridspertise is currently supporting E-distribuzione in the study and development of architectures for the control of microgrids. Investigation activities are ongoing as part of the Italian project ISMI (Integrated Storage and Microgrid Innovation), headed by E-distribuzione and targeting the control of the network stability in the scenario of Italian small islands, whilst making more efficient the conventional generation sources and favoring the penetration of renewable ones.

The paper follows with a first general introduction of the Gridspertise laboratories, provided in Sec. II. Then, in Section III, a more specific description of the setup of the LV Smart Grid Laboratory follows, with focus on the components implementing the control functionalities and algorithms in study in the ISMI project. Finally, in Section IV a brief description of the activities involving remote co-simulations of the Smart Grid Laboratories with third party ones is provided.

II. GRIDSPERTISE LABORATORIES

Gridspertise relies on several laboratories to bring innovation to the market and develop global as well as specific solutions. The laboratories are located in Italy, Spain and Brazil. With reference to the Italian Smart Grid Laboratories, they are arranged to perform research and development activities on smart grids. They are located in Milan and Bari and focus on medium (MV) and low voltage (LV) level grids respectively. The two laboratories reproduce the "Grid in a Building" concept by integrating real time digital simulators, which emulate electric power systems, with devices operating protection, control and monitoring functionalities, as well as other power devices emulating loads, generators, renewable power plants and energy storage systems. The equipment is suitably interconnected to perform hardware-in-the-loop (HIL) and power-hardware-in-the-loop (PHIL) studies. IEDs are interconnected and configured to reproduce automation procedures to be operated in the real field conditions. Additionally, it is possible to emulate any operating scenario where the DSO operating staff could be trained on the functionalities of the field devices, as well as on the operations of the control room.

A preliminary description of the setup of the two laboratories has been given in [6], where the test infrastructure, the earliest smart grids devices and the first communication tests based on the IEC 61850 standard have been presented. The following evolution of both laboratories has been reported in [7], with a focus on the architecture for the remote control, protection and management of the MV and LV smart grids. Still, new devices and technologies are expanding the assets, pushed by the evolution of smart grids

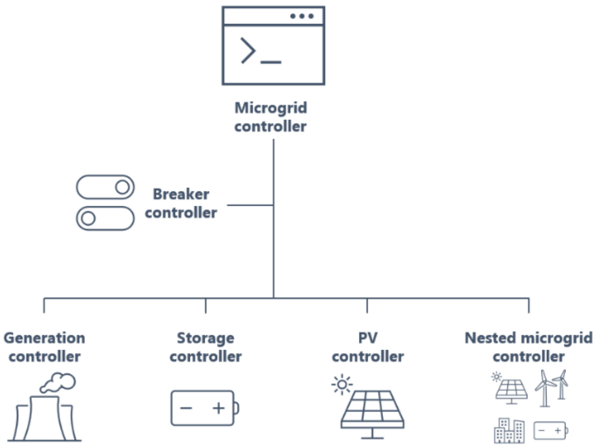

Fig. 2. Hierarchical control architecture of the test microgrid.

as well as the needs emerging from ongoing and upcoming research projects.

In the following, the paper focuses on the new setup of the LV Smart Grid Laboratory supporting the investigations in scope of the ISMI project for the definition of a control architecture suitable for Italian small islands grids. The architecture is based on the integration of control strategies operated at a global network level by a Microgrid Controller, as well as at a local level by controllers of renewable and conventional generation sources and energy storage systems.

III. LV Laboratory setup

The LV Smart Grid Laboratory is structured in two segments, the power and the digital one, with a common core determined by a real time power grids digital simulator. The power segment emulates a LV grid branch to perform PHIL simulations. Its configuration has been mainly described in [7].

The digital segment of the LV Smart Grid Laboratory consists of the power grids digital simulator and of different standardized IEDs and prototypes. It is mainly exploited to perform research and development activities in HIL mode. Currently, part of this laboratory section has been set up to simulate a test microgrid, in order to demonstrate the effectiveness and stability of the architecture proposed with the ISMI project. The management intelligence of the test microgrid is performed by means of physical devices suitably programmed, configured and integrated with the microgrid, to form part of the control architecture.

The following subsections describe more in detail the three main components of the digital segment, set up for the study of microgrid control architecture, namely the real time power grids digital simulator, the smart grid controllers and the digital substations. The overall scheme of the communication infrastructure is shown in Fig. 3.

A. Test microgrid and RTDS

A test microgrid has been simulated, having as reference the real scenarios of isolated microgrids present on the Italian small islands. The microgrid representation is shown in Fig. 1. The microgrid operates on two different voltage levels, 10 kV (MV) and 0.4 kV (LV). Specifically, the MV distribution network consists of an open ring and includes five secondary MV/LV substations. The LV networks, not shown in the figure, unfold from secondary substations and include customers passive loads, as well as small (<10 kW) diffuse generation sources. The microgrid is mainly fed by a power station composed by four diesel generating units and a battery energy storage system. On the MV level, an additional storage unit, a photovoltaic power plant, a MV customer and a nested microgrid (prosumer) are connected too.

The Real Time Digital Simulator (RTDS) has been used to digitally emulate the test microgrid [8]. The RTDS exploits the computational capabilities of superscalar multi-core microprocessors to numerically solve modelled electric power grids. The laboratory is equipped with four RTDS racks, i.e. hardware units composed of processor and electrical and network communication interfaces. Specifically, two of the racks are NovaCor™, the latest hardware platform available by RTDS Technologies Inc. The other two racks are from the previous generation, based on the so-called PB5 processor cards. The usage of the four available racks can be sized based on the level of detail of a simulation. When three or more racks are available, the communication among them is orchestrated by the Global Bus Hub (GBH) component and is supported by fiber optic connections.

A relevant aspect related to the use of real time simulators is the possibility to benefit of HIL simulations, in which physical devices performing smart grid automation functionalities (e.g., power system protections and control devices) interact with the real time simulated power system to test and analyze their behavior in real field-like conditions. The interaction between the RTDS and the physical devices is achieved through different digital and analog (±10 Vpp) electrical input/output cards (labelled as GTDI/O and GTAI/O respectively in Fig. 3), as well as network communication-based cards (GTNET, in Fig. 3) that can handle data exchanges based on different standards and protocols. Electrical connections could pass through signal adapters, for devices working on small voltages or currents, like in the case of 4…20 mA standard signals (see Sec. C). Other devices, like energy meters or metering units onboard of PLCs, require power inputs obtainable by using power amplifiers.

B. Smart grid control

The control of the test microgrid is achieved by a hierarchical architecture with two-levels, a local and a global one.

At the lower level, control units have been defined in correspondence of each generation or storage plant, in order to obtain local observability and controllability. In particular, these control units, referred hereinafter as Plant Control Units (PCUs), actually correspond to standardized physical interfaces normed by the Italian regulation and currently mandatory for plants with a relevant (>1 MW) production component [9]. Their introduction in the regulatory landscape was dictated by the need of increasing the observability of the distribution system for both the Transmission and Distribution System Operators. Furthermore, in the proposed architecture, they include regulation capabilities to support the DSO in the management and operation of the distribution network. Among the regulation functionalities, we mention the (a) active power limitation, (b) modulation of the imported / exported active power, (c) voltage regulation by supplying inductive / capacitive reactive power, (d) power factor setpoint, (e) reactive power regulation as function of the

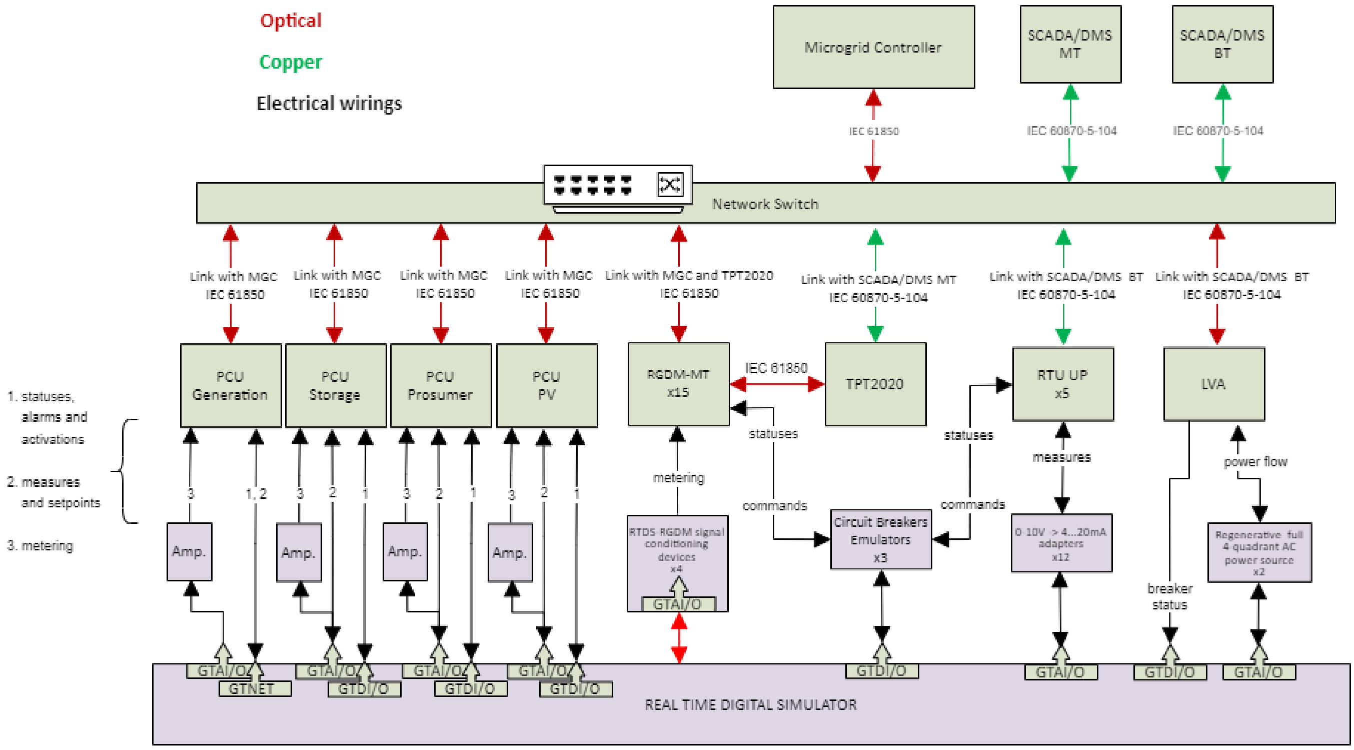

Fig. 3. Scheme of the communication infrastructure. Red lines are used for fiber optic connections, green for copper and black for electrical wire ones.

voltage, (f) power factor regulation as function of active power, (g) active and reactive power setpoint in import and export for the dispatchment market service. For a generic generation / storage plant, it has been considered here that the enabling of a regulation function could be established with an agreement between the owner of the power plant and the DSO.

Regarding the higher control level of the architecture, the monitoring and coordination roles are managed by a central controller, namely the Microgrid Controller (MGC), that operates as a supervisor having a global view of the microgrid. It monitors and coordinates the various local control units accordingly to the classical microgrid hierarchical control architecture, as proposed in the IEEE 2030 standard [10]. A schematic picture of the control architecture is provided in Fig. 2. More in detail, the MGC functionalities include: (a) the collection from the PCUs of metering data related to the underlying generation and storage plants, such as powers, voltages, currents and state of charges, as well as information about the availability to operate regulation functionalities and the corresponding operative states, (b) the operation of circuit breakers, (c) the monitoring of the general state of the entire microgrid and (d) the execution of a control algorithm to automate the dispatching of the power contributions over the available generating / storage units to increase the safety of microgrid.

It is worth noting that centralized and distributed control units are configured to operate on different time scales. Specifically, distributed control units operated on the scale of the seconds whereas, the central control unit runs on the scale of the minutes. As a matter of fact, the whole architecture operates simultaneously secondary and tertiary control actions, whereas the primary controller of each generation / storage unit of the microgrid is implemented in the RTDS model, onboard of each power plant.

To implement the units of the control architecture, several Programmable Logical Controllers (PLCs) have been set up and their interface configured both with the RTDS, for the PCU-plant integration, and among them, for the MGC-PCU integration. Specifically, the devices installed are modular input/output and control solutions. The PLCs interface configuration consists of: (a) networking modules used for the logical communication between the MGC and the PCUs (IEC 61850 MMS standard messages) and between the PCUs and the RTDS (Modbus/TCP) as well; (b) metering modules for the collection of electrical power signals and the generation of measures and (c) digital and analog I/O modules for the exchange of statuses and activations as well as measures and setpoints between the PCUs and RTDS, as shown in Fig. 3.

An example response of the microgrid frequency is shown in Fig. 4, observed in the RTDS as a consequence of a generation curtailment command received through the control chain MGC-PCU-generation unit (PV, in this specific example) to manage overgeneration risks.

C. Digital substation

The set of physical devices needed to emulate the microgrid automation is completed with the ones implementing the functionalities of a digital substation. The setup includes: RGDMs (i.e. measuring, protection and automation devices for MV substations), UPs (secondary substation RTUs) and one TPT2020 (primary substation RTU). MV and LV Distribution Management Systems (DMS) and SCADAs are also integrated in the architecture to receive real time measurements and signals from the microgrid, as well as to send remote commands to the IEDs.

The circuit breakers behavior has been emulated by using programmable automation controllers. They exchange informative and control signals with the RGDMs, the UPs and the RTDS. In the RTDS simulation, the circuit breaker states

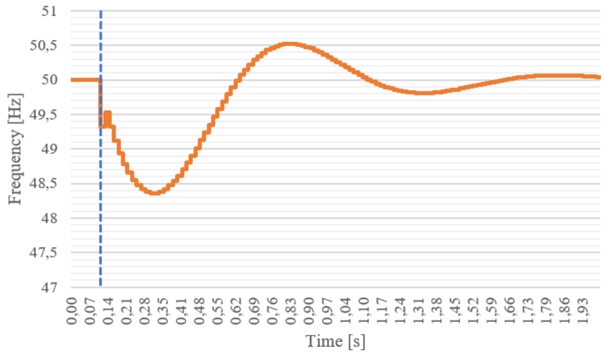

Fig. 4. Frequency response of the microgrid generated by the RTDS, following a variation of the load-generation balance. The blue dashed line shows the instant of the change in balance.

are acquired consistently, and controls can also be sent for setting up possible operating scenarios.

RGDMs are installed in correspondence of remotely controlled secondary substation circuit breakers, present in fifteen points of the test microgrid, i.e. inside the secondary substations, on sides where the MV backbone departs and where relevant MV generation plants are connected. Each RGDM is connected (a) electrically to a circuit breaker and (b) logically to a TPT2020 and to the MGC, using IEC 61850 MMS standard messages. We point out here that a peer-to-peer IEC 61850 Goose message-based communication is also generally used among RGDMs to implement automation intelligence for fast grid restoration. The latter functionality is currently not provided in the setup, as it has been considered non-relevant for testing the MGC and PCUs proposed control architecture. RGDMs are also electrically connected to the RTDS, each receiving three node voltages and three line currents from the power grid installation nodes. The RTDS-RGDM integration presents different points of attention. First, due to the number of RGDMs connected (fifteen), several RTDS analog output cards need to be used. To optimize the occupancy of the limited RTDS module interfaces, we used a daisy chain configuration for the analog output cards. Second, the large number of signals to be exchanged between the RTDS and the RGDMs requires a solution to optimize the resulting wiring. Third, the input connectors to RGDMs are based on RJ45 connectors bringing voltage signals proportional to field voltage and current [11]. Fourth, the input voltage dynamic of the RGDM is two orders of magnitude smaller compared to sine waves generated by RTDS analog output cards, that would be affected by a relevant quantization error component. In order to solve the last three points, a solution was developed to (a) bring the signal sources, i.e. the analog output cards, close to the RGDMs; (b) obtain a clean RJ45 wiring; (c) reduce the noise due to the quantization error by using resistive voltage dividers to scale down the sine waves generated by RTDS. The signal conditioning device prototyped consist of RTDS analog output cards enclosed in metallic cases and connected to the RTDS by using a fiber optic connection, with voltage dividers circuitry installed on their output. The connection between the signal conditioning devices and the RGDMs is based on short and equal length Ethernet cables, suitable for the transmission of signals ranging in hundreds mV dynamic.

Five UPs are located in correspondence of each of the secondary substations, with the goal of (a) sending to the MV SCADA information about the state of the circuit breakers and the electrical measures collected on the network and (b) allowing direct remote-control operations on controllable circuit breakers. Control operations ordered by the control room operators through the MV SCADA are received by the proper UP via IEC 60870-5-104, that in turn routes the command to the circuit breaker. The UPs also provide 4…20 mA inputs to collect LV lines power flows, which are generated by the RTDS simulation, properly adapted by means of transducers.

The primary substation RTU TPT2020 is used to collect electrical measures from the microgrid through the RGDMs, conveying them to the MV SCADA. Furthermore, in addition to UPs capabilities, TPT2020 provides a second way of executing remote operations ordered by the control room operators on circuit breakers. Redundancy is thus achieved by using this configuration, increasing the control architecture fault tolerance. The communication between the TPT2020 and the RGDMs is based on the IEC 61850 MMS, while the communication with the MV SCADA is based on the IEC 60870-5-104 standard.

Finally, a new smart grid device prototype is going to be integrated in the architecture, namely the Low Voltage Agent (LVA). The LVA will introduce monitoring, protection, remote control and automation functionalities on the LV network nodes, allowing a finer grained metering and more specific management of the microgrid. The IED will communicate with the LV SCADA and with the MGC, using IEC 60870-5-104 and 61850 standards, respectively. To integrate the LVA in the test infrastructure, we are planning to use two regenerative full four-quadrant AC power source driven by RTDS analog output cards, in order to impress the voltage and current of a specific monitored LV node of the microgrid, characterized by the presence of downstream distributed generations sources.

IV. Remote Simulations

The laboratory setup is evolving to allow remote integration with other simulation sites geographically distributed. The complexity of smart grids and related functionalities, as well as the wide extension of the distribution networks and their large number of elements to be modelled and simulated could require, in view of advanced studies, the exploitation of high performing grid simulators and a great number of IEDs.

In Enel, first remote simulation tests among different laboratories were observed in the Living Grid research project, where PHIL co-simulation assessments were carried out, connecting the laboratories of the Polytechnic Universities of Bari and Turin [12]. Currently, research teams of the “Innovation Hub & Lab” of EnelX and the “LabZero” of the Polytechnic University of Bari are involved in remote simulation activities with E-distribuzione and the Gridspertise LV Smart Grid Lab. Multiple VPN tunnels are being implemented in order to establish the communication among the laboratories. The connections will bring us several advantages. First of all, an increase of the computational capabilities that will allow a finer modelling of certain parts of the system, whose complexity could have impacts on the overall system stability and control strategies. Second, we will have the possibility to study scenarios integrating components operating at different hierarchical levels, time scales or physical voltage levels. Third, the possibilities to test devices and to integrate portions of specialized software would be extended by exploiting, respectively, the Remote-PHIL and the Remote-SIL (Software-in-the-Loop). Fourth, the co-simulation with other companies and research institutions will facilitate the collaboration and the mixing of the expertise, while keeping at the same time confidentiality on sensitive data or models. Eventually, the laboratories interconnection will also avoid new heavy investments on simulators and IEDs and allow to maximize their use.

V. CONCLUSIONS

The laboratories represent a well-established starting point to provide advanced solutions and support the DSO, where new devices and technologies for the digitalization of network infrastructures and field operations, as well as for metering, are designed, developed and tested, and flexibility services offered.

In order to have cutting edge solutions, E-Distribuzione and Gridspertise are continuously strengthening their know-how and capabilities in the fields of smart grids and digitalization of electricity distribution networks. In this context, the Gridspertise contribution extends from the prototyping of smart-grid IEDs up to their validation, integration and operation in control and automation architectures. These research and development activities are allowed and reinforced by the MV and LV smart grid laboratories, suitably arranged to accommodate and integrate state-of-the-art and new prototyped smart-grid IEDs operating protection, control, automation and monitoring functionalities. This paper provided a description of the LV Laboratory setup, with a focus on the control and automation architecture proposed for improving the stability and efficiency of isolated or weakly connected microgrids. The setup comprises IEDs implementing the main control, automation, protection and monitoring functionalities, integrated in PHIL configuration with a real time power grids simulator. The hardware is used and configured to provide advanced control and automation solutions for complex scenarios like those represented by small-islanded grids, where the missing connection with the main continental power system makes proper operations harder to achieve.

Some IEDs currently composing the proposed control and automation architecture, as the PCUs and MGC, have been prototyped by Gridspertise team in the collaboration environment of the ISMI project. In the incoming future, other specialized IEDs with similar functionalities will be provided by the project partners, to be integrated in the test infrastructure.

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