

Power Hardware-in-the-Loop tests of a control architecture for isolated microgrids in a co-simulation framework

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Abstract—Climate change and ambitious goals, such as energy transition and carbon neutrality, require a massive integration of Renewable Energy Sources (RES). However, the intermittent and stochastic nature of RES makes net-load profiles more unpredictable. Unexpected fluctuations in RES power output encourage radical changes in the planning and operation of power systems, that must evolve towards the smart grid concept. In such a scenario, small non-synchronous electrical networks are more likely to face stability issues due to RES penetration, since they are characterized by low rotational inertia. Moreover, as the energy transition encourages Distribution System Operators to redefine the approach to power system operation, even new tools are needed to quickly and effectively deploy the most suitable technological solutions. This is required both to reduce the long testing phases on the field and to make investments more effective. In this regard, the paper presents the results of an ongoing collaboration between e-distribuzione, Gridspertise and Politecnico di Bari which have set up a Remote Power Hardware-in-the-Loop co-simulation platform. Benefits and shortcomings of such cooperative framework was evaluated considering and testing the control architecture deployed to guarantee a secure operation of islanded distribution networks in the frame of the Italian ISMI project.

Index Terms—remote power hardware-in-the-loop (R-PHIL), co-simulation, islanded microgrid, hierarchical control architecture, operating reserve, non-synchronous power system.

I. INTRODUCTION

Climate change and carbon neutrality goals require a shift from an energy mix based on fossil fuels to one that produces very limited carbon emissions. For this reason, in the actual electrical grid planning and operating scenario, a massive integration of renewable energy sources (RES) is expected. The integration of distributed energy resources (DERs) in old-conceived power systems is drastically changing the paradigm of the traditional power systems where electricity was centrally produced in large conventional plants and reaches passive customers through transmission and distribution grids. Moreover, the aleatory nature of RES production profiles involves several challenges in operational aspects of power systems [1], like protection and control. Furthermore, DERs are usually

connected to the main grid through power electronic converters which are unable to provide physical inertia to the system and increase the injection of harmonic components [2].

Such challenges are much more demanding for non-synchronous power systems, which are generally characterized by low rotational inertia and large seasonal load variations [3]. In these operating contexts, in the absence of suitable control strategies for the available resources, the RES penetration is often limited in favour of the thermal generating units that have to cover the relevant energy demand. Clearly, by limiting the exploitation of the RES potential, some of the main advantages arising from their higher penetration come less, such as the reduction of carbon emissions and operational costs related to the fuel and its provision [4], [5].

Several papers proposed solutions to enable greater penetration of RES on small islands. For example, [6] and [7] proposed to enhance power quality on islands through innovative energy resources such as public lighting systems and flywheels, respectively. Furthermore, [3] and [8] propose predictive optimization algorithms to guarantee a safe operation of islanded networks while reducing related costs. Both papers considered the provision of operating reserve as crucial to reliably operate non-synchronous power systems with high RES penetration. Likewise, the authors in [9] proposed a hierarchical control architecture for islanded distribution networks aimed at increasing the hosting capacity of such grids, while guaranteeing a safe operation of the system.

However, just as innovative solutions are needed to deal with challenges due to the intermittent nature of RES, even new tools must be adopted to speed up the testing and commissioning of the deployed technologies. The duration of test phases and fielding of new technological solutions can be reduced by adopting Remote Power Hardware-in-the-Loop (R-PHIL) co-simulation platforms. Such a tool permits the involved parties to remotely share hardware and software facilities located in different laboratories, while maintaining the control on their own algorithms, models and technologies. Thus, such

a solution facilitates the cooperation and the management of the intellectual property aspects of the involved technologies.

In this regard, Gridspertise, an affiliate company of Enel Group, and Politecnico di Bari have collaborated to implement a R-PHIL real-time co-simulation platform to assess benefits and shortcomings of cooperative simulation frameworks. The deployed R-PHIL set-up allowed also to consolidate the testing phase of the control architecture described in [9], which was developed in the frame of the Italian ISMI (Integrated Storage and Microgrid Innovation) project headed by e-distribuzione, the main Italian Distribution System Operator (DSO).

Gridspertise's grid-technology team, in the LV Smart Grid Lab in Bari, assembled a real-time Hardware-in-the-Loop (HIL) simulation environment to model and simulate the MATLAB/Simulink reference test case considered in [9]. The arranged simulation platform comprised some of the hardware and software facilities mentioned in [10]. On the other hand, LabZERO's research group at Politecnico di Bari set up a real-time Power Hardware-in-the-Loop (PHIL) framework to emulate the power behaviour of a prosumer. The deployed simulation framework is made up of some of the LabZERO microgrid components [11]. Consequently, the prosumer's power response is measured at LabZERO and integrated into Gridspertise's HIL simulation at the PCC.

In this paper, a preliminary overview of the control architecture adopted is presented. It follows a brief description of the Gridspertise's HIL laboratory set-up implementing the control architecture. The R-PHIL with the LabZERO set-up is subsequently presented. Then, test results on the deployed R-PHIL co-simulation set-up are presented. Firstly, loopback tests allowed to evaluate the latency and the quality of the designed communication framework are illustrated. Finally, the power response of the LabZERO's microgrid has been integrated in the Gridspertise's simulated model, and test results on the deployed control architecture are presented.

II. CONTROL ARCHITECTURE FOR ISLANDED DISTRIBUTION NETWORKS

The aleatory nature of RES leads to unforeseen fluctuations in net-load profiles. Although robust systems, like continental interconnected ones, are less susceptible to such uncertainties thanks to the large inertia of rotating machines, smaller non-synchronous power systems could suffer for high level of RES integration due to their low rotational inertia, and could experience instability issues. Therefore, islanded distribution networks, like those on small islands, constitute an ideal test bed for testing the integration of innovative technological solutions deployed to face stability issues due to RES penetration.

In the wake of research on microgrids control, e-distribuzione, Gridspertise and Politecnico di Bari are still collaborating in the frame of the ISMI project. Such collaboration permitted to deploy a control architecture aimed at increasing the hosting capacity of Italian small islands. The solution, described in [9], consists of a hierarchical control architecture that comprises monitoring and control elements already diffused in Italian electrical networks. The proposed

control scheme is derived from the structure of the IEEE 2030 standard for microgrid controllers [12], which is based on three control layers, namely, primary, secondary and tertiary.

In such control scheme, the primary control layer comprises all the functionalities operated by the local level controllers, such as speed governors and excitation current regulators of thermal units, as well as droop techniques required to share power contributions for voltage and frequency regulation.

The secondary layer of the architecture is decentralized and can be identified in breaker controllers (BCs) and plant control units (PCUs). Breaker controllers are able to provide measuring and protection functionalities. Specialized devices that provide such capabilities are already diffused in the Italian grids in correspondence of secondary substation MV feeders, i.e. RGDMs (directional fault detector and measuring devices) and Remote Terminal Units (RTUs). Plant control units are designed to collect measures and states from single generating units or their aggregation, in compliance with the Italian standard CEI 0-16 [13] which requires such functionalities as mandatory for generating and storage units with rated power greater than 1 MW. For this reason, in [9], the PCUs are assumed to be associated to each relevant generation and storage unit. Besides monitoring functionalities, the standard also requires controlling capabilities (i.e. active power limitation, modulation of the imported/exported active power, voltage regulation by supplying reactive power, etc.) to be available through PCUs. In [9], the authors assumed that the availability of some of the controlling functionalities (i.e. active power limitation) is made mandatory and further functions, currently not considered in [13], like spinning reserve provision, are available for islanded scenarios.

On the tertiary layer, a central Microgrid Controller (MGC) collects measures and status from the lower level, processes such inputs through a dedicated algorithm and dispatches control actions (i.e. commanding operations and sending set-points) to the abovementioned BCs and PCUs. The MGC algorithm is drawn to assess the operating reserve provided by the available resources, in order to verify the adequacy of the system. Namely, the deployed algorithm evaluates if the available upward and downward reserves are sufficient to withstand any sudden net-load variation. Whenever the system reserve is not enough to sustain such variations, the MGC elaborates and dispatches control actions to preemptively provide the missing reserve, while satisfying technical limits of distributed resources. Since in [9] the algorithm is deployed through a finite-state machine, in each operating state the adequacy of the system is checked under specific conditions. Different control actions are elaborated and transitions between different operating states occur when conditions are not satisfied.

III. HARDWARE-IN-THE-LOOP SET-UP FOR TESTING THE CONTROL ARCHITECTURE

The Gridspertise's LV Smart Grid Lab in Bari has been arranged to host a physical implementation of the control architecture described in the previous section. A complete description of the laboratory was presented in [10]. The set-up

is mainly composed by automation and protection devices, i.e. RGDMs and RTUs, that have been integrated with the digital real-time simulation model of a reference islanded distribution network. Two RTDS Novacor racks numerically solve the modelled electrical grid allowing real-time simulations.

A schematic representation of the modelled electrical network is shown at the bottom of Fig. 1. The microgrid mainly consists of five secondary MV/LV substations (SS#1, ..., SS#5) and is operated on two different voltage levels, 10 kV (MV) and 0.4 kV (LV). Customers are supplied by LV networks that depart from each secondary substation. The MV network is typically operated in open ring configuration, although a switch disconnector (between SS#1 and SS#5) allows the reclosure in case of fault events or maintenance.

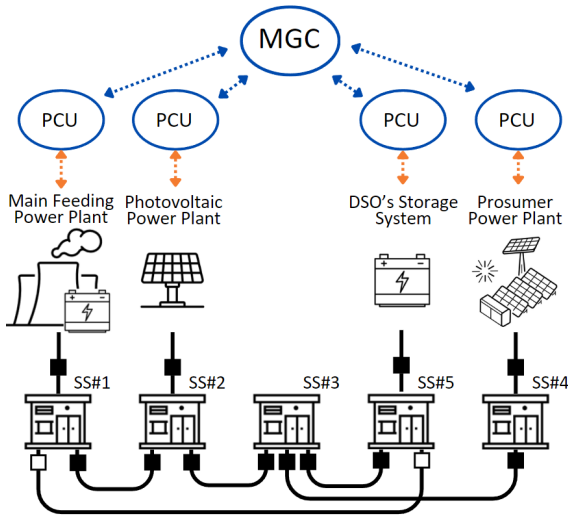


Fig. 1. Schematic representation of the simulated electrical distribution network and the deployed control architecture framework.

Passive (lines, transformers, etc.) and active (diesel generators, prosumer, BESS, etc.) components within the network are emulated through equivalent software models. Moreover, the simulation includes the primary control layer of the architecture through the modelling of speed governors, excitation current regulators of thermal units, and inverters with voltage and frequency droop mechanisms. Regarding the generation units in the simulated microgrid, the main feeding power plant is connected to SS#1 and is composed by four 480 kW diesel generators and a 500/600 kW/kWh battery energy storage system (BESS). Further DERs are connected to other substations, namely a 100 kW PV power plant is connected to the SS#2 and a 200/200 kW/kWh BESS is connected to the SS#5. An industrial prosumer has been considered and connected directly to the SS#4.

The real-time simulation computes voltage and current waveforms at each electrical node. The RTDS sends them to the electronic devices composing the described architecture through analog and digital I/O modules and network communication-based boards which can handle different communication standards and protocols, i.e. Modbus, IEC 61850.

As introduced in Section II, the two upper levels of the control architecture are performed, locally, by BCs and PCUs and, centrally, by the MGC. Specifically, at the local level, programmable logic controllers (PLCs) were programmed to act as PCUs in correspondence of each generation and storage power plant, to ensure local observability and controllability, as required by CEI 0-16. Further hardware facilities were exploited in the set-up to introduce automation, protection and monitoring functionalities of MV substations, i.e. RGDMs and RTUs for Distribution Management Systems (DMS) and SCADAs integration. These systems contribute to define the centralized level of the deployed control architecture. They allow the reception in the control room of real-time measurements and signals from the controlled microgrid, as well as to send remote commands to on-field installed intelligent electronic devices (IEDs), adopting the IEC 60870-5-104 standard. In addition, on the centralized control layer, a further PLC has been programmed to operate the functionalities of the MGC described in Section II. It communicates with PCUs and BCs through IEC 61850 MMS messages.

IV. REMOTE POWER HARDWARE-IN-THE-LOOP SET-UP

As described in the previous section, the HIL simulation at LV Smart Grid Lab comprises only devices dedicated to control and protection purposes, i.e. RGDMs, RTUs and PCUs. Energy producers and customers, instead, have been simulated through RTDS software models. With the aim of evaluating the effectiveness of the actions of the deployed control architecture under real power forcing, Gridspertise and Politecnico di Bari collaborated for the setting up of a cooperative R-PHIL co-simulation platform to introduce real power responses within the simulated microgrid. In such a simulation framework, HIL facilities at LV Smart Grid Lab allow the execution of real-time simulations of the islanded distribution network depicted in Fig. 1. Meanwhile, the research group at Politecnico di Bari exploited hardware and software facilities in the LabZERO's microgrid to arrange a Power Hardware-in-the-Loop (PHIL) simulation set-up which reproduces the power behaviour of a prosumer. A complete description of the LabZERO was presented in [11]. In this work, the LabZERO's PHIL set-up consists of an OPAL real-time digital simulator, which is interfaced with a real microgrid through a Triphase power amplifier module that is controlled in voltage source mode and exploited to impose the voltage amplitude (V) and frequency (f) at the microgrid's power busbars. The microgrid is composed by two load banks and a controllable BESS connected to the same power busbars. The formers have been used to emulate unexpected variations in the prosumer's internal active power consumption and production. Instead, the BESS' power response was controlled by a local PID controller tuned to satisfy commands enforced by the connected PCU, to meet step-response requirements for active power limitation, in compliance with the CEI 0-16. The control action elaborated by such controller is calculated and sent to the BESS' management system by the real-time simulator.

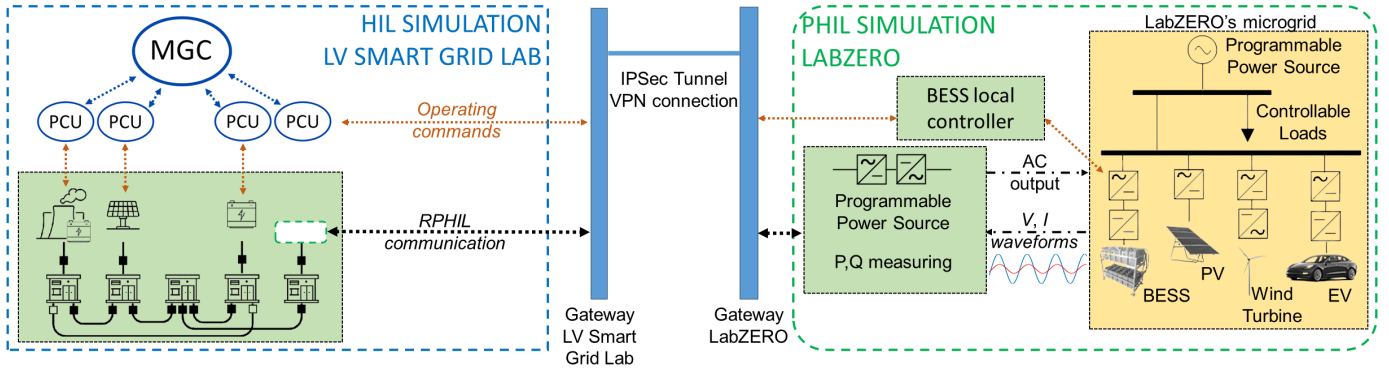


Fig. 2. Schematic representation of the deployed Remote Power Hardware-in-the-Loop co-simulation platform.

In the deployed R-PHIL co-simulation platform, the above-mentioned LabZERO's components have been exploited to replace the RTDS software-based prosumer's model connected to the SS#4 of Fig. 1. As depicted in Fig. 2, a VPN-based connection has been established between the gateways of the two laboratories. Thus, the voltage conditions measured at the prosumer's PCC in the Gridspertise's HIL simulation are reconstructed at LabZERO's busbars through the OPAL-Triphase set-up. Likewise, the P and Q measured by the LabZERO apparatus are sent to the LV Smart Grid Lab to control the power response of an equivalent source emulating and replacing the prosumer model, previously modelled in the RTDS environment and connected to SS#4.

V. TEST RESULTS

Before testing the control architecture detailed in Section II, the quality of the communication of the R-PHIL co-simulation platform have been evaluated through loopback tests. Further R-PHIL simulation tests allowed to evaluate the reliability of the deployed control architecture by analyzing the power response of a real prosumer remotely interfaced with the simulation. The analysis consisted of verifying that the prosumer's power output had been correctly limited through its own PCU after receiving specific commands by the MGC.

A. Loopback test

Loopback tests consisted in generating a sinusoidal signal – disturbed with a pulse every second – on one of the hosts of the co-simulation, LabZERO's OPAL in this case. Then, generated data were translated and sent through UDP messages to the gateway at LV Smart Grid Lab by LabZERO's one. Finally, Gridspertise's RTDS transmitted back the received message, closing the loop with the sender. Fig. 3 shows that such signals, sampled and sent to the LV Smart Grid Lab every millisecond, came back to LabZERO with a delay of about 50 ms.

The obtained results highlighted that real-time communication of sinusoidal waveforms cannot be feasible through the designed communication platform. For this reason, co-simulation tests on the deployed control architecture have been carried out considering phasorial quantities, such as active and reactive power, RMS values of voltage and frequency.

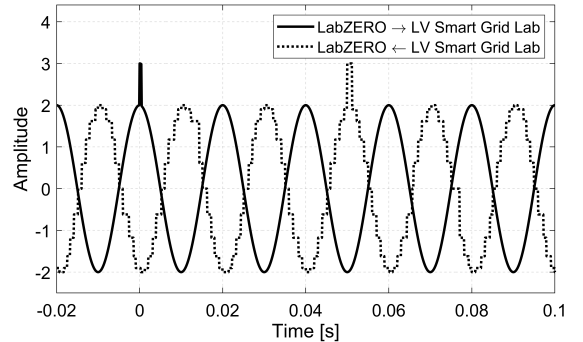


Fig. 3. Test signals from Politecnico di Bari to the LV Smart Grid Lab (continuous) and vice versa (dotted) during loopback tests.

B. Remote Power Hardware-in-the-Loop co-simulation test

In this section, test results on the control architecture described in Section II are presented. Such results have been obtained adopting the R-PHIL co-simulation platform depicted in Fig. 2, where the dynamic behaviour of the prosumer at SS#4 in RTDS simulated network is emulated by the physical response of LabZERO's microgrid apparatus. In particular, the two load banks at LabZERO's laboratory allowed to reproduce the power production of a 100 kW PV plant and the power demand of the emulated prosumer. It is worth noting that, since the purpose of this test was to evaluate the performance of the R-PHIL set-up by considering control actions on the prosumer unit, the BESS at SS#5 was intentionally disconnected from the simulated grid. Thus, the LabZERO's prosumer became the only resource available to the MGC to increase the downward operating reserve availability, which is strictly related to the production of the thermal plant at SS#1. Consequently, the conducted tests aimed at evaluating the actual power response of such prosumer whose power output has been locally limited through its own PCU, after receiving specific commands by the MGC. The curves in Fig. 4 depict the available and the required downward reserve over the test intervals (#A, #B, #C, #D, #E) and used by the MGC to evaluate its control actions. The resulting MGC's limitation set-points and the prosumer's active power injection at SS#4 are depicted in Fig. 5.

At the beginning, Gridspertise's HIL simulation and

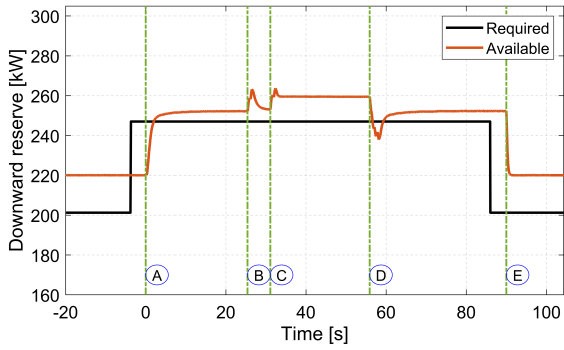


Fig. 4. Required (black) and available (orange) downward reserve levels.

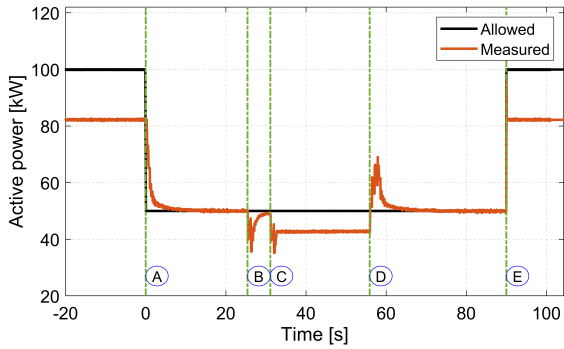


Fig. 5. Allowed (black) and measured (orange) prosumer's injection.

LabZERO's PHIL simulation are synchronized in a steady-state condition. Indeed, for $t < 0$, the prosumer injects 83 kW at the PCC, and the voltage conditions measured at LabZERO's power busbars are the same calculated at SS#4 in the HIL simulation at LV Smart Grid Lab, as shown in Fig. 6.

According to Fig. 4, slightly before $t = 0$ s, the downward reserve required by the MGC to withstand any unforeseen net-load fluctuation becomes greater than the thermal unit's power production, namely, the available downward reserve. Therefore, in #A ($t = 0$ s), the MGC detected such reserve deficit and decided to limit the prosumer's injected power for making thermal plant's production higher, and so to procure the missing reserve. It should be pointed out that the MGC evaluates the operating state conditions every 90 seconds. For this reason, the MGC's limitation set-point calculated in #A, and depicted in Fig. 5, is a little delayed with respect to the sudden rise in the required downward reserve drawn in Fig. 4. Since the shortage amounted to 27 kW, the output of the prosumer should have been limited from 83 kW to 56 kW. However, the Italian standard CEI 0-16 [13] states that the limitation of RES active power production must be imposed through discrete intervals of 10% of generators' rated power. Thus, in #A the MGC demanded the prosumer's PCU to limit the active power injection into the grid from 100% to 50% of the power plant's capability (100 kW), yielding the prosumer to inject 50 kW maximum. The prosumer's PCU received such operating command with about 25 ms of delay because of the communication latency. Once the command is

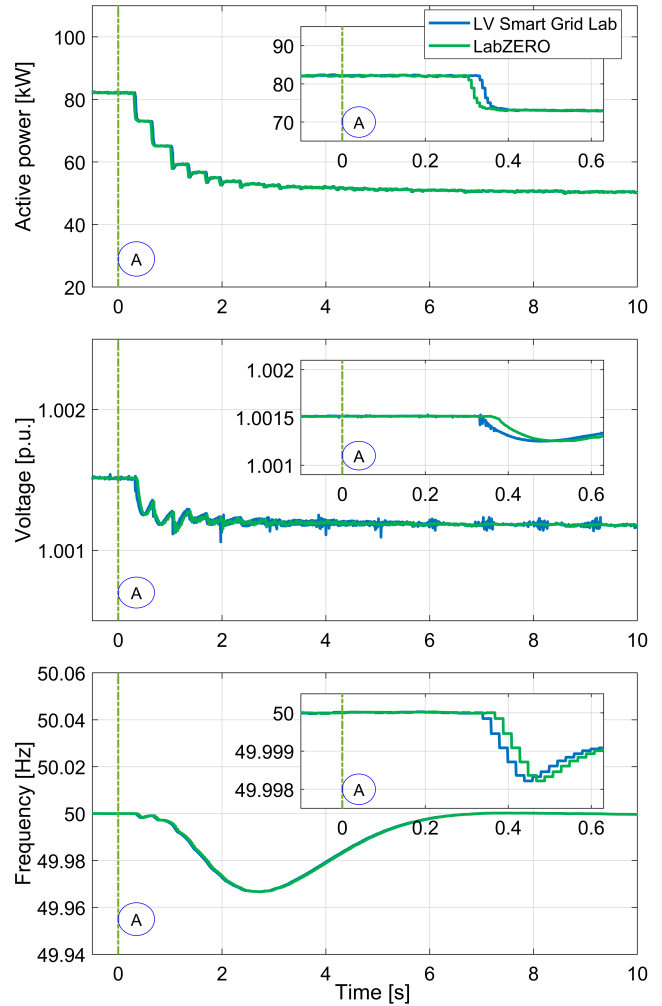


Fig. 6. Active power (top), voltage amplitude (middle) and frequency (bottom) measurements at PCC (at LV Smart Grid Lab in blue, at LabZERO in green).

received, the associated PID controller regulated the charging power of the LabZERO's storage to satisfy the MGC's request. For the same time interval #A, the Fig. 6 depicts the active power, voltage amplitude and frequency profiles recorded at both sides, namely, the PCC simulated at the LV Smart Grid Lab and LabZERO's busbars. The figure shows that the local controller deployed at LabZERO is able to modify storage's power response to meet the maximum allowed injection in less than 10 s. The obtained response satisfies step-response time requirements - 10 to 600 s - in compliance with the Italian standard CEI 0-16 [13]. The active power and voltage curves in Fig. 6 show that variations in the prosumer's power response do not immediately involve voltage fluctuations at LabZERO's busbars. It is because V and f set-points do not get updated by RTDS until Gridspertise receives the P and Q measurements by Politecnico di Bari. Conversely, power and voltage profiles evolve simultaneously at SS#4 in the simulated model. Therefore, voltage variations at LabZERO's busbars occur as soon as the V and f set-points calculated by the RTDS reached the LabZERO's real-time simulator and the controllable voltage

source. The delay between the power responses and the voltage profiles at the PHIL node (LabZERO's busbars) is inevitable, since the latency of the remote connection. Although the dynamics under investigation were characterized by a response time comparable with such latency, the simulation could be affected in terms of accuracy. However, the aforementioned issue concerns electromechanical transients studies at most, so the observed delay and related effects can be neglected.

In the successive time interval #B, the testing scenario moves towards further prosumer's operating conditions. In particular, in this time interval the variation of the prosumer absorbed power have been emulated through connection and disconnection of resistive loads on the LabZERO's bank loads. Such variations have been introduced in order to evaluate the effectiveness of the deployed control architecture even when power fluctuations or unforeseen faults occur.

Firstly, in #B, the load consumption within LabZERO microgrid increased by 20 kW. Thus, the local controller regulated the storage's charging power to meet the active power limitation set by the MGC. A few seconds later, in time interval #C, the microgrid's load demand increased by further 20 kW, reaching an overall rise of 40 kW from the initial state. Since the microgrid's PV was producing 83 kW at the beginning, the prosumer's power injection reached about 43 kW. For this reason, the constraint enforced by MGC is automatically satisfied at this stage, and no regulation of the storage's charging power is needed. Nevertheless, the limitation set by MGC is still enforced and the system is always promptly ready to regulate the storage's power response to satisfy such request. Indeed, in #D, the local controller regulated the storage's output to limit the active power injection at SS#4 after a local load reduction. Therefore, the limitation enforced in #A allowed to satisfy reserve requirements during the entire test. Such control action has been called off at the next MGC control cycle, in #E, when it detected that the needed reserve returned to its initial value.

VI. CONCLUSION

In the frame of the ISMI project presided by e-distribuzione, a R-PHIL co-simulation platform has been arranged by the Gridspertise's grid-technology team in Bari and the LabZERO's research group of the Politecnico di Bari. In this work, the tests involved both the HIL setup at the LV Smart Grid Lab and the LabZERO's PHIL setup. The Gridspertise's setup allowed to perform real-time simulations on a reference islanded distribution network, whose resources are managed according to a hierarchical control architecture designed to guarantee a safe operation of non-synchronous power systems. The components in the LabZERO's setup permitted to reproduce the real power response of a microgrid, that replaced the software-based model of a prosumer in the Gridspertise's HIL simulation through a VPN-based communication.

According to the obtained results, remote co-simulation platforms offer several advantages, although the accuracy of the real-time co-simulation strictly depends on the quality of

the established communication. Firstly, they enhance computational capabilities, enabling more precise modelling of specific system components whose complexity could affect overall system stability and control strategies. Secondly, remote co-simulation enables the examination of scenarios that involve components operating at varying hierarchical levels, time scales, or physical voltage levels. Thirdly, collaborating through co-simulation with other institutions promotes knowledge and expertise sharing, while maintaining confidentiality on sensitive data and models. Lastly, interconnecting laboratories eliminates the need for substantial investments in new simulators and specialized components, allowing the maximization of their utilization.

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